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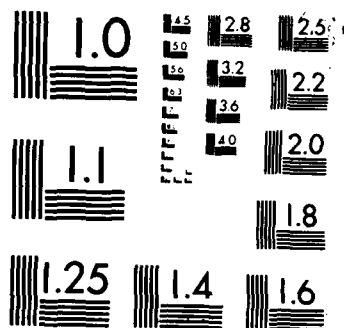
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Suspended Sediment Dynamics of Lake Cumberland, Kentucky

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Lake Cumberland receives a heavy sediment load during storm events. In some years significant amounts of suspended sediments have traversed the entire length of the reservoir to cause high turbidity levels in the lake and in outflows from Wolf Creek Dam. In other years most of the particles have settled out of the water column and outflows have remained relatively clear. The release of turbid water has a detrimental impact on water quality conditions in the tailwaters and downstream navigation impoundments.		

The survey described in this report was undertaken to develop a better understanding of phenomena affecting suspended sediment dynamics in Lake Cumberland. The knowledge acquired will serve as a basis for developing predictive techniques which can be used to forecast potential problems and study means of alleviating these problems.

The survey included the collection of data from Lake Cumberland at monthly intervals during the March through August period in 1983. Samples were collected from six sites on the lake and one site in the tailwaters. Parameters measured in situ or elsewhere on the same day the sample was collected include temperature, turbidity, number and size of particles, and particle charge or zeta potential. Samples returned to the laboratory were routinely analyzed for total, dissolved, and suspended solids. In addition, samples from the more turbid layers were analyzed for volatile suspended solids and x-ray diffraction tests were performed to characterize the nature of the particles comprising the suspended sediments.

The information acquired about sediment dynamics was evaluated with knowledge of lake hydrodynamics to describe the movement of suspended sediments in the impoundment and effects on turbidity.

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SUSPENDED SEDIMENT DYNAMICS OF
LAKE CUMBERLAND, KENTUCKY

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SUSPENDED SEDIMENT DYNAMICS OF LAKE CUMBERLAND, KENTUCKY

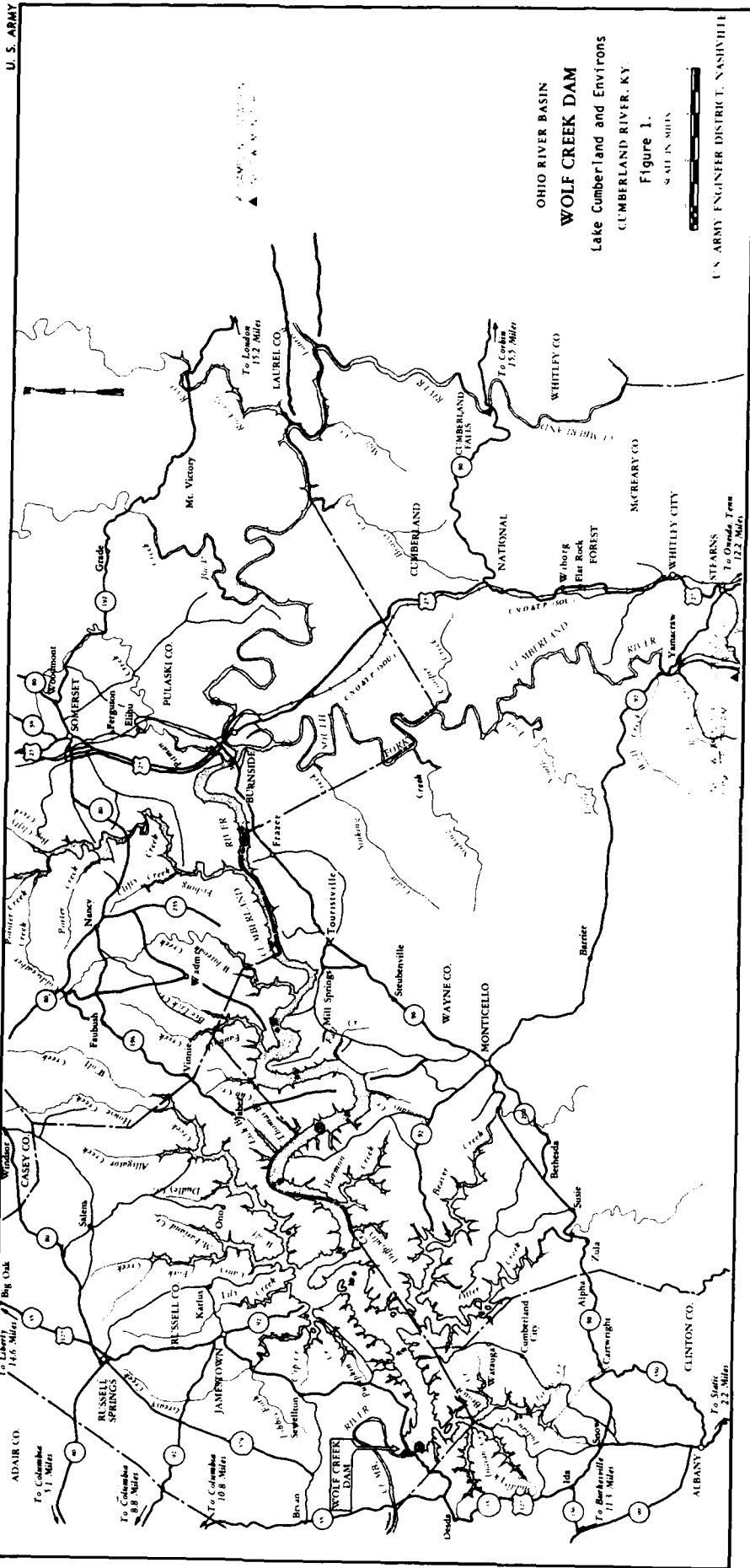
PART I: INTRODUCTION

1. Lake Cumberland is located in Southeast Kentucky on the Cumberland River. The lake's 101-mile length lies within six counties and drains an area of 5,789 square miles as shown in Figure 1. As with other reservoirs, water flowing through Lake Cumberland slows and is retained for long periods within the lake prior to release to the downstream river. This decrease in velocity usually allows any solids which have been suspended within the more turbulent flow to fall to the lake bottom as sediment. Lake Cumberland has an average hydraulic retention time of approximately 215 days which should be adequate in most cases to allow any suspended particles to settle out [1]. In the case of Lake Cumberland, however, it has been noted on several occasions that the water released from Wolf Creek Dam has had a higher level of turbidity than the surface waters retained above the dam [2]. Since the natural settling process does not appear to reach completion during storage, it is suspected that some physical or chemical property of the particles prevents the natural settling process from reaching completion.

2. Turbidity measurements have long been utilized as a means to evaluate water quality. The chemical and physical properties of a lake in turn influence the diversity of the food web and the stability of the system as a whole. Although there appeared to be few ill-effects resulting from the turbidity in and released from Lake Cumberland in

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1983, there are problems which need to be examined along with reevaluation of some basic principles of lake management.

3. The possible problems which this turbidity represents are in its connection to biological productivity. It is widely known that the more valued game fish species require high water quality. High levels of turbidity interfere with feeding by these species. The release of turbid water from Lake Cumberland is partly responsible for turbid conditions in Cordell Hull Lake and may be partly responsible for the failure of the trout fishery which was desired by many agencies and citizens [2].

4. Suspended particles also serve as attachment sites for aquatic microorganisms. While Lake Cumberland is phosphorus limited, the existence of these available sites reduces light penetration and with addition of phosphorus might promote some changes in the lake's trophic status.

5. In recent years, the agencies involved in lake and reservoir management have placed growing emphasis on the ability of reservoirs to "treat" inflowing waters and improve overall chemical quality. However, the types of surveys necessary to establish these treatment results have not always been performed. This has often led to the need for guesswork, rather than data, when describing the specific effects of impoundments on water quality.

Purpose

6. The purpose of this water quality survey was to examine the turbidity phenomenon within Lake Cumberland in an attempt to gain better understanding of the suspended sediment dynamics of the impoundment.

The formation and characteristics of the turbidity layer and its progress through the lake were tracked to evaluate the treatment ability of the lake. Measurements of physical and chemical parameters were taken and examined for particle content with relation to depth. Specific parameters included electrical charge, size distribution, and mineral composition of the particles. In addition, more routine water quality parameters were measured.

Scope of Survey

7. Six data collection trips were made to Lake Cumberland between March and September, 1983, at approximately monthly intervals. A total of seven sampling stations, one immediately downstream of Wolf Creek Dam, and six sites within the lake were chosen so as to sample along the length of the lake and the primary inflow of the tributaries.

8. At each station, samples were collected at twenty-foot intervals from the surface to within a few feet of the lake bottom at the deepest point of the cross-section. These samples were analyzed on the same day for turbidity, number and size distribution of particles, and particle charge. After returning to the Tennessee Technological University laboratory, the samples were examined for total, dissolved, and suspended particle content. In addition, in situ measurements were made at 10-foot intervals of water temperature, dissolved oxygen content, pH, conductivity, and oxidation-reduction potential at each station. The assembled information of each collection trip was then forwarded to the Hydrology and Hydraulics Branch, Engineering Division, Nashville District, Corps of Engineers where the data were entered into a computer data file. Using the Corps' water resources plotting

programs, profiles of the data were then plotted for each of the measured parameters over the length of the lake.

9. After the completion of the final sampling trip, the data were examined in detail to determine the physical or chemical properties which were involved in maintaining particles in suspension. Additionally, the measured parameters were evaluated for their importance as analytical tools and their interrelationships.

PART II: LITERATURE REVIEW

10. In order to understand the possible reasons behind the continued suspension of particles within Lake Cumberland, a thorough review of the characteristics of suspended particles was necessary. A knowledge of the basic concepts behind the various water quality tests and an examination of suspended particle dynamics was also required. Additional understanding was also obtained by a review of previous studies dealing with similar problems or testing methods.

Colloidal Systems and Suspension Stability

11. Colloidal systems occur when finely divided discrete particles are dispersed in a continuous medium. For the purposes of this review, the particles will be in a solid form and the medium a liquid. In general, colloidal systems are composed of particles ranging from one nanometer or millimicron (1×10^{-9} meter) to one micrometer or micron (1×10^{-6} meter) [3]. Systems with particle sizes greater than one micron are termed suspensions [4]. There is some disagreement on the classification of particles within a transition zone ranging from 1 to 100 microns. This interval is also called the supracolloidal fraction [5]. Since natural waters tend to contain a wide range of particle sizes, the terms colloidal system and suspension will be used interchangeably for convenience.

12. There are two types of colloidal systems which occur in water. These are hydrophilic where the particles are strongly bound with water and hydrophobic where this binding does not exist.



Hydrophilic colloids might be characterized by substances such as proteins, soaps, and synthetic detergents while hydrophobic colloids include such things as gold, clay, and other metals [3].

13. Although most hydrophilic particles have a slightly negative charge, this is not their primary source of stability. Hydrophilic colloids depend on their affinity or binding ability with water to maintain stability. They also usually serve as protective colloids by enveloping hydrophobic particles. In this way, the hydrophobic colloids are shielded from the action of any electrolytes present which greatly reduces the coagulation which would normally occur [6]. There is much less information concerning hydrophilic colloids due to the prevalence of hydrophobic colloidal systems in nature.

14. Hydrophobic colloids have an electrical charge which provides stability due to the repulsive forces of like charges. Most colloids which occur naturally consist of negatively charged particles. Since a colloidal dispersion does not have a net electrical charge, the charge of the particles must be counterbalanced for electroneutrality to exist. This is accomplished by ions of opposite charge (counter-ions) being attracted to the colloidal particles to produce an electrical double layer. Hydrophobic colloids may obtain their charge in two ways. Some preferentially adsorb certain ions on the particle's surface which then constitute the inner coating of the electrical double layer. These adsorbed ions are called peptizing ions. Other hydrophobic colloids obtain their charge from imperfections in the particle's structure. This is especially common in clays where imperfections in the crystal lattice structure result in unsatisfied bonds. The outer coating of the electrical double layer consists of counter-ions which accumulate around

the hydrophobic colloid to offset its charge. This attraction of counter-ions causes the electrical potential present on the particle surface to decrease to zero at some distance from the particle [3].

15. Outside of this double layer or fixed layer, a layer of diffused ions exists where the forces of electrical attraction and diffusion compete. Diffusion occurs in response to thermal agitation on the loosely held ions within this layer while electrical attraction holds counter-ions within this layer over which the net charge of the particle is still in effect. The thickness of the diffuse layer increases with lower ion concentrations and decreases with higher ion concentrations within the solution [6]. Located approximately at the outer perimeter of the fixed layer is a shear plane or shear surface. This shear plane represents the outer perimeter of the particle plus the outer layer of fixed counter-ions and any water molecules bound to these counter-ions, all of which move with the particle. The remaining unbalanced charge at the shear surface appears to be the main cause of the particle's stability. This electrostatic potential at the shear plane, which is also dependent on the distance from the particle over which the charge is effective, is called the zeta potential. A large zeta potential provides greater stability since the repulsive forces between the particles would be stronger over a greater distance. Figure 2 demonstrates the location of the fixed double layer, diffused layer, and shear plane around a typical hydrophobic colloidal particle. The charge of the particle over distance is also presented showing the zeta potential [5].

16. The repulsive force of a colloid's zeta potential is counteracted to some degree by an attractive force called van der Waals'

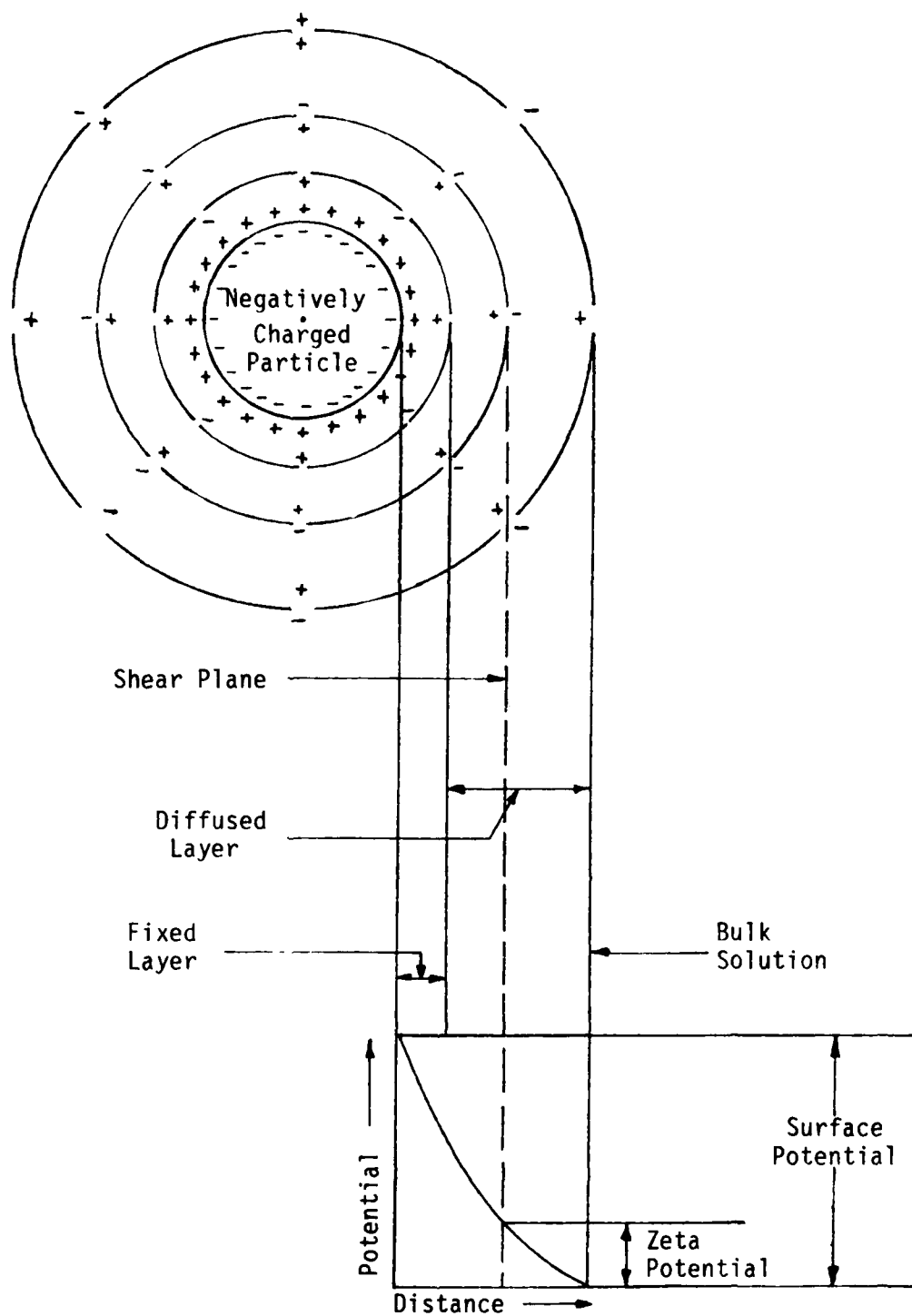


Figure 2. A Negatively Charged Colloidal Particle with Its Electrostatic Field

force. Van der Waals' forces are those forces of attraction which exist between bodies regardless of charge or composition. This attraction is a function of the density of the bodies being affected and decreases rapidly with increasing distances between the bodies. This is because the attractive energy acting between the two particles is inversely proportional to the distance between them squared [3]. In the case of colloids, the attractive forces have been measured and are of the right magnitude and range to compete with the electrokinetic repulsive forces [7].

17. The forces of attraction and repulsion due to zeta potential and van der Waals' force can be plotted and a curve showing the net force exerted determined. This curve usually takes the form of an energy hump or hill which represents a net repulsive force to within a short distance from the particle's surface. Very near the surface, the strength of van der Waals' force becomes much greater than the repulsive force and the resultant net force becomes one of strong attraction [3].

18. The opportunity for these forces to come into play between particles in a colloidal system is due to the phenomenon of Brownian motion. This random movement of particles is caused by the constant bombardment of the colloid's small mass by molecules within the dispersion medium. Whether the particles remain in stable suspension or coagulate to form larger particles which may settle out depends upon the magnitude or height of the energy hump which must be overcome before attraction can occur. Because van der Waals' force is determined by the density of the particles which remain constant, the zeta potential of the particles must be reduced if coagulation is to occur. It was

previously indicated that the distance over which a charge extends can be changed by manipulating the ionic concentration of the liquid. Since the zeta potential is defined as the charge in effect over distance from the particle's surface, it can be reduced by changes in ionic concentration. This will, in turn, effect the height of the energy hump or barrier of the resultant net force curve as is demonstrated in Figure 3.

Particle Suspension Due to Other Causes

19. In addition to the colloidal systems discussed, particles may be suspended by other causes. One of these causes which is also involved in colloidal systems is the size of the particles in question. It was noted that the literature is not always in agreement on the exact size limitations of colloidal systems versus suspensions. While this division can be made arbitrarily, the related classification of settleability is based upon a large number of variables which combine to either cause suspension or allow settling. Figures 4 and 5 have been provided in order to establish the particle sizes which are being examined and their classification ranges [8,9]. Of special importance in these figures is the fraction of particles ranging from 1 to 10 μm which are not colloidal or settleable.

20. It should be pointed out that these classifications are not binding as many variables are involved. In many cases where the particles may be settling, the settling velocity may be so slow that the particles appear to be stably suspended. An example of this slow settling phenomenon can be seen by releasing kaolin particles having diameters of 2 μm into water. The particles settle at a rate of

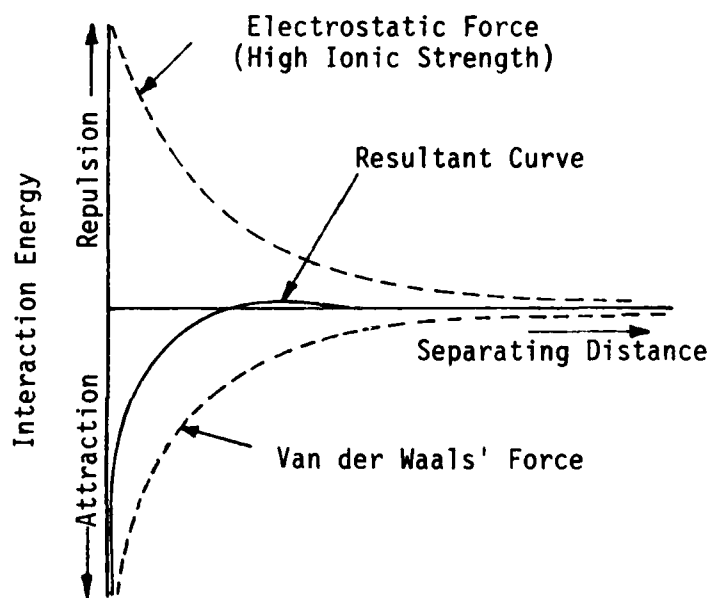
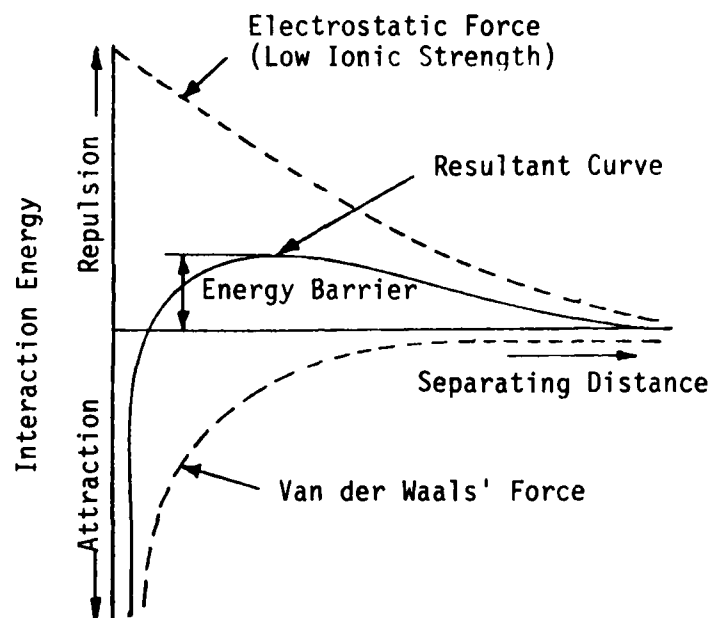


Figure 3. The Effect of Ionic Strength and Separating Distance on the Forces of Interaction Between Colloids

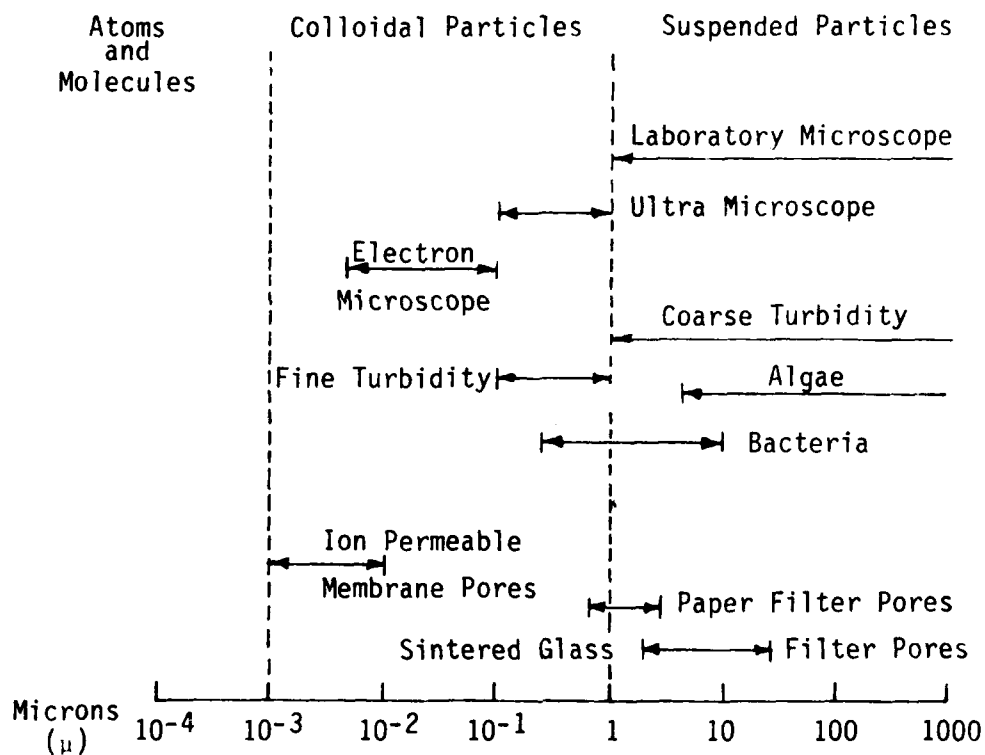


Figure 4. Classification of Dispersed Systems

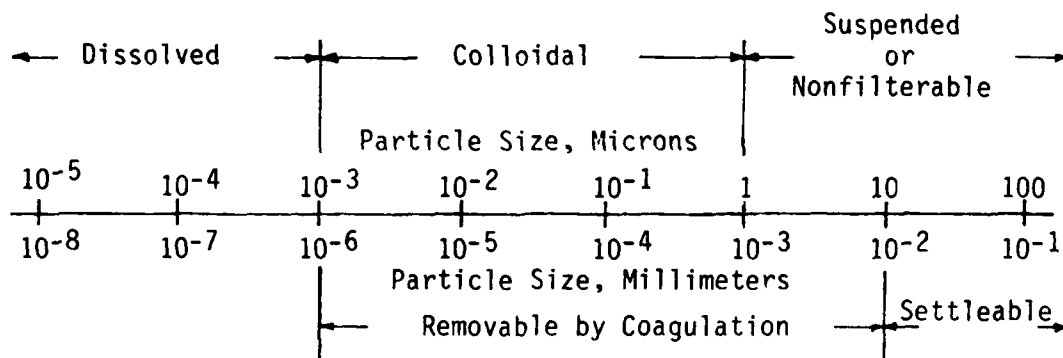


Figure 5. Classification and Size Range of Particles Found in Water

approximately 1 cm per hour [10]. Figure 6 displays a graph of calculated settling velocities versus particle size for a specific type particle [8]. From these two examples, it is clear that particles might appear suspended even in lakes having long retention times.

21. Various equations have been developed to estimate the velocity at which particles settle in a liquid. Newton's equation takes into account such variables as particle volume, mass and density, liquid density, gravity, the area of the particle projected against the direction of flow, and a dimensionless drag coefficient [11]. Calculated results from Newton's equation appear to closely approximate experimental data for particles down to about 1 mm in diameter. The most commonly used formula for determining settling velocities for smaller particles is Stokes' equation. Experimental data for diameters ranging from approximately 10 to 100 microns tend to follow Stokes' equation [12].

22. Additional variables which affect settling velocity include fluid viscosity, shape, roundness, and surface texture or roughness of the particles [13]. There are also factors related to either the particle or the fluid which can cause changes in settling velocity. These include turbulence, particle rotation, boundary conditions, and multiparticle influences. Boundary conditions refer to changes brought about when the particles are in close proximity to a surface boundary such as a channel wall. Multiparticle influences can either speed or slow settling velocity. In the case of a few closely spaced particles, the speed increases while for many dispersed particles, or high concentrations, the fall velocity is reduced. This decrease for particles in high concentrations is called hindered settling [12].

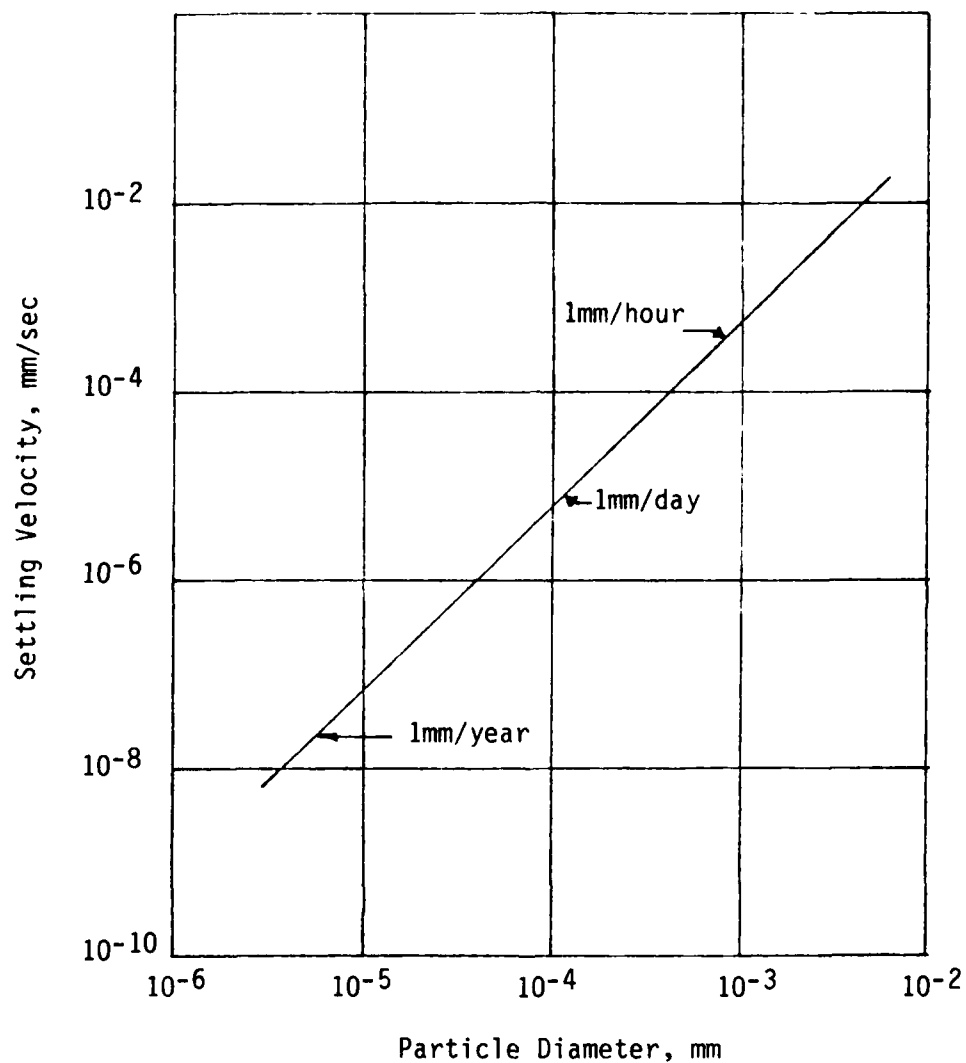


Figure 6. Settling Velocities of Spherical Silica Particles in Still Water Computed from Stokes' Law (Specific Gravity = 2.65, Temperature = 15°C)

23. Because of the large number of variables involved, there has not been sufficient work done to determine the exact settling velocity for particles having every combination of variables possible. Experimental work has been primarily aimed at improving the commonly used equations by the use of adjusting factors in order to approximate experimental results. The results of such experiments are usually reported based on particle size with little reference made to any other variables. This leads to a wide range of settling velocities being reported in the literature for the same size particles. The range of sizes over which a modeling equation holds is also clouded by these secondary variables. For example, in the case of Stokes' equation, it has been found applicable only to particles greater than 4 to 5 μm . However, the variables involved here are very important, being at depths greater than 300 meters and in ocean water [14]. This would suggest that there is also a lower limit to which Stokes' equation is applicable in fresh water. The limit would exist where the density, size, and pressure variables of the saltwater system equaled the slowing effect of a combination of variables in a freshwater system.

24. The size range of 1 to 10 μm has already been noted as being neither colloidal or settleable. This appears to correspond to the situation at Lake Cumberland. According to Figure 4, some of the materials available to produce turbidity within this size range include algae, bacteria, and coarse turbidity. Since algae and bacteria are organic and thus volatile, their presence can be determined quickly by testing for volatile suspended solids. The coarse turbidity classification, however, may contain a wide range of possible nonvolatile inorganic minerals in the form of sediments. Organic

particles other than living organisms might also be included but these should be easily identified since they are not normally present in natural waters as a continuous component of turbidity.

25. The mineral sediments have been classified according to the type of sediment and its size range. These classes are presented in Table 1 [15].

Table 1. Sediment Classifications

Class	Size, μm
Boulders	> 256,000
Cobbles	64,000 - 256,000
Gravel	2,000 - 64,000
Sand	62 - 2000
Silt	4.0 - 62
Clay	0.24 - 4.0

From these size ranges, it is clear that the sediment classes most likely involved at Lake Cumberland include the clays and finer silts. It must be remembered, however, that this classification system is based on size and not on the actual composition of particles in each size range. While the system was developed to differentiate between materials by their sizes, other substances might be found within the same size range. Now that the definition of these terms which refer only to particle size has been clarified, the material composition definitions need to be examined.

26. Clays are produced by the alteration of minerals as rocks weather due to chemical leaching by rain, surface runoff, and

groundwater. The time required for clay minerals to be produced by this process is so great that it is measured geologically. The crystalline structure of clay minerals was proven by x-ray powder photographs in 1930 by the U.S. Department of Agriculture. After World War II, the use of wide-range goniometers on x-ray units allowed for rapid identification of the various clay minerals [16].

27. The basic building blocks of clay minerals are two-dimensional arrays of silicon-oxygen tetrahedra and two-dimensional arrays of aluminum- or magnesium-oxygen-hydroxyl octahedra. The various clay minerals are composed of these tetrahedral and octahedral sheets superimposed in different fashions. The symmetry and dimensions of the tetrahedral and octahedral sheets permit the sharing of oxygen atoms. These are called two-layer minerals. Three-layer minerals are also found with the octahedral sheet between two tetrahedral sheets [7]. The one group of clay minerals which are not layer-lattice silicates is the Palygorskite-Sepiolite group which are chain silicates [16].

28. Silt differs from clay in a number of important areas. The area per unit weight of clay ranges from 10 to 1,000 m² per gram as compared to 0.1 to 1 m² per gram of silt. This is significant since the adsorption of water, nutrients, and gases are all surface phenomena. The shape of silt particles is irregularly fragmented and seldom smooth or flat like the plate-like clay particles [17]. Silt particles are in reality microsand particles with quartz being the dominant mineral along with primary minerals which have escaped weathering such as feldspar and mica. The principal chemical component of silt is silica which constitutes from approximately 65 to 90 percent of the material. A major difference between silt and clay can be seen in the reaction of

each with water. Silt allows fairly free movement of water and air. When water is added to clay particles, they absorb the water, swelling and increasing in volume. Clay also retains a film of water on the particle's surface [18].

29. There are a number of other minerals commonly found within the size range of 1-10 μm . In addition to feldspar and quartz which have already been mentioned, dolomite, calcite, iron oxides, and zeolites may be present [16]. There also exists an entirely different category of material known as amorphous material.

30. Amorphous material is defined as solid particles having neither recognizable shape or geometrical internal structure [19]. Although these characteristics are completely different than those of clay, some references consider amorphous minerals to be a type of clay [16]. Amorphous material was produced in two ways: true amorphous minerals which originally formed in the noncrystalline state either by rapid cooling from a molten state or by the slow hardening of a gelatinous material; and metamict minerals which formed originally as crystalline compounds in which the crystalline structure was later destroyed [20].

31. Since amorphous material does not react to x-ray diffraction as do crystalline minerals, other methods have been developed to chemically determine their composition. Usually amorphous materials tend to contain the same elements as commonly found in clays, such as silica and alumina [21]. It was perhaps this fact which led many of the early investigators to believe that the occurrence of amorphous material was somewhat rare [22]. It is interesting to note that while early researchers considered essentially all natural

silicates to be crystalline, amorphous silicates are formed when precipitated from aqueous solution. This result is thought to be due to the size distribution of the polysilicate ions usually found in solution. Because of their nonuniform sizes, these polysilicate ions cannot arrange themselves, when combined with metal ions, to form a regular crystal lattice [23]. Over a period of time, it has been determined by the use of the electron microscope and x-rays that inorganic amorphous substances are commonly found in nature [24]. In fact, a wide range of materials exist between the two extremes of crystalline and amorphous minerals. Many materials also exist as a combination of amorphous and crystalline where grains of different sizes and minerals are bonded together [19].

32. The lack of structure found in amorphous material is important when considering settling velocities. The crystalline structure represents an orderly and relatively dense packing arrangement of the molecules involved. Since amorphous structures are not orderly, open areas tend to occur between the molecules. This results in a difference in the weight of crystalline versus amorphous particles of the same composition and size. For example, amorphous silicon dioxide has a specific gravity of approximately 2.2 as compared to the range of approximately 2.4 to 2.9 for various clays and other minerals [25]. Although this difference seems minor, when inserted into settling velocity equations its importance becomes clear. In nature, the result of such a change could reduce the settling velocity of a particle in combination with other variables to the point that the particle may either remain suspended or be resuspended by wave action produced by wind or motorboat activity.

Case Studies

33. A review of the particles and the factors which contribute to particle suspension would not be complete without looking at examples of these particles in their natural settings. The dynamics of lakes and reservoirs which may contribute to suspension are also examined by a review of documented occurrences.

34. Clay turbidity is a common problem in many lakes, rivers, and ponds. When suspended, clay particles restrict light penetration and limit photosynthesis. Fish eggs and benthic communities may also be destroyed if covered by settled clay particles. Although not economical on large bodies of water, methods have been examined which precipitate clay turbidity economically from ponds. In a recent study, aluminum sulfate, or alum, was used successfully to remove clay turbidity from ponds used for fish farming. Alum and other electrolytes have been widely employed by environmental engineers to remove clay turbidity from water supplies. The alkalinity and toxicity to the fish were checked and the results indicated no significant problems until the alum doses reached rather large proportions [26]. Using the same principle of increasing electrolyte concentration to reduce the repulsive force between particles, another study used CaCl_2 and MgCl_2 to flocculate suspensions of four types of clays commonly found in California soils. From the information gathered on each clay, their respective critical salt concentrations (CSC) required to produce flocculation were determined [27]. It is important to remember that the economics of treating a body of water depends primarily on the volume of water to be

treated, how often this treatment may be required, and the benefits expected from treatment.

35. In order to prevent the suspension of these small particles in natural waters, it is necessary to determine where they originate and how they are produced. The major nonpoint source of sediments is cropland which contributes about fifty percent of the sediment delivered to the streams and lakes of the United States. This results in approximately 1.8 billion metric tons annually. Cropland erodes at a rate 168 times that of commercial forests. Even when harvested, these forests produce only eleven times the erosion of their uncut condition [28]. A study was conducted on a watershed area in West Virginia to determine the effects of clearcutting on water quality. It was determined that clearcutting had a negligible effect with turbidity showing only slight increases after storm periods. This lack of adverse effects on water quality was attributed to a combined program of careful road management, retention of a forest strip along the stream banks, and rapid, lush revegetation after clearcutting [29].

36. The removal of these particles appears to be a two-phase operation with water being the causative agent in both phases. First the detachment of the particles is brought about by the impact of raindrops. The particles are washed into and plug the surface pores which can then no longer drain the water into the soil. The second phase occurs when water accumulates at the surface and begins to move downslope as runoff carrying with it the particles continuously being detached by the raindrop impacts. The size of these particles have been studied along with their means of removal. It is interesting to note that two to four times the amount of material less than 2 μm was removed

by wash as compared to the effects of splash. Also important was the fact that the percent of wash material in this size range was less than one-fourth of the percent found in the original soil. In fact, the results consistently showed that the clay content was eroding away at a slower rate than the other components of the soils tested. These results were considered to be important for two reasons. First, because of their expanding lattice structure, clay has a high carrying capacity for pollutants, and second, clay stays in suspension virtually as long as the water is moving [30]. The results showing the clay particles to be the least eroding portion of the soils tested is very important since clays are the most common cause of turbidity in water. This result is even more important when considering the fact that smaller particles generally require lower dosages of coagulant [31].

37. Since most turbidity is introduced by runoff after rainstorms, it is possible that the influx of turbidity is a seasonal occurrence linked to weather patterns. This is only partly true. A study performed on a lake in New York found that during winter and spring overturn and a portion of fall mixing, the turbidity rose due to inorganic particles. This result might be attributed to the increased concentrations with increased depth becoming remixed. The study also found that during the summer, the turbidity increased due to the contribution of algal blooms [32].

38. In the absence of coagulation, it has been determined that the concentration of particulate matter increases with depth from the epilimnion, through the thermocline, and hypolimnion for a lake in a steady-state condition. This is due to the effect of temperature on fluid viscosity. With the temperature decrease from epilimnion to

hypolimnion, the fluid viscosity may double and in turn cause a reduction in the Stokes' settling velocity by nearly fifty percent. This condition is not commonly observed because some degree of coagulation usually occurs [33]. A similar situation was observed and further explained by a study of some Japanese lakes. In this case, suspended sediment gradings were found to exist where fine particles were distributed over a layer with increasingly larger particles located at greater depths [34]. This vertical gradient with depth has also been observed to a lesser degree in the turbulent waters of the Amazon River [35].

39. Another form of suspended sediment gradation occurs in almost all large bodies of water. This is a horizontal gradient where upon entering, the inflow contains suspended sediment having a large average particle size. As the flow moves slowly toward the outlet, the larger particles settle out along the way. This results in a decrease in the average particle size over distance through the lake or reservoir. In the case of a controlled outlet, the operation of the outlet will most likely dictate the flow patterns in the lower portion of the lake which, in turn, affects both the time a flow is retained allowing its contents to settle and the turbulence which might maintain particles in suspension [36]. These longitudinal gradients are very closely related to the hydrodynamics of the impoundment and are characteristic of long narrow lakes [37]. This same principle is employed by environmental engineers in the design of rectangular settling basins for water and wastewater treatment.

40. Since the outlet of a reservoir can affect the hydrodynamics or flow patterns upstream in addition to strongly

influencing the characteristics of the water which is released downstream, most dams are now being built with multilevel outlets. By control of the various outlets, the temperature and turbidity of the water released can be successfully regulated. A measure of control over upstream hydrodynamics can also be obtained by use of multilayer withdrawal capability. Release from low levels can produce scour and remove particles which have settled out [38]. An example of this scouring ability can be seen in the operation of Guernsey Dam, Wyoming, where the upstream hydrodynamics were manipulated to restore the reservoir's volume which had been lost due to sedimentation [39].

41. A number of other phenomena in the upstream portion of a reservoir can greatly influence the hydrodynamics of the outlet region near the dam. Density currents or flows, turbidity currents, and plunging phenomena may all contribute to affect the hydrodynamics of a lake.

42. Density currents or flows occur due to the presence of density gradients with depth in a body of water. When a flow of uniform density, due to either suspended sediment or temperature, enters such a stratified body, the flow tends to insert itself at a level equal to its density. This inserted water disperses itself quickly as a current, or flow, laterally and over the length of the lake to form a thin layer. The inflow could insert itself above the existing layers resulting in a density overflow, beneath the existing layers resulting in an underflow, or between existing layers for an interflow. A study conducted on DeGray Lake, Arkansas, found all types of density flows present at different periods [40].

43. Turbidity currents are simply density currents which are heavily sediment laden. The occurrence of turbidity currents has been observed for nearly one hundred years in locations throughout the world such as Lake Geneva, Lake Mead, Nevada, and Lake Superior. In Lake Mead, the velocity of these turbid flows, many of which traverse the entire length of the lake, can average up to 25 cm/sec [41]. At these velocities, suspended particles are not allowed to settle out. Experiments have shown, however, that non-channelized turbidity currents deposit their sediments when their velocity slows upon entering a larger body of water. The turbidity flow disperses horizontally in a 90° angle with the greatest velocity over the center 40° portion which in turn transports the most sediment. The sediment is deposited over a fan-shaped area with decreases in mean grain size diameter and deposit thickness with increasing distance from the inlet [42].

44. Density interflows and underflows are the result of incoming water inserting itself into an established stratified gradient of a lake. Since most inflow arrives at relatively high velocities from surface inlets, at some point the entering water must adjust to its own density layer. The location where the inflowing water is displaced downward, or plunge point, occurs where the buoyant forces of the existing surface waters exceed the velocity or inertia forces of the inflow [37]. A plunge point is sometimes marked by changes in turbidity or accumulation of floating debris, indicating the point where opposite movement of surface waters occurs [40].

45. The use of reservoirs to treat natural waters has been mentioned before. Usually the size of lakes and reservoirs precludes the economical use of electrolyte treatment for turbidity removal.

Employing a lake or reservoir as a natural large-scale settling basin, however, has been demonstrated to be somewhat successful. In order to operate a system so that the optimum treatment or desired outflow properties are attained, a complex set of variables including multiple outlets, plunge points, density or turbidity currents, inflow and outflow requirements, and many others must all be either controlled or predicted. To be able to maintain all of the variables and recognize their interactions, computer modeling is required. A number of different programs have been developed to predict results of hydrological events. One such program was developed to predict the temperature, suspended sediment concentrations, and reservoir trap efficiency for Lake Chicot, Arkansas, based on meteorological, hydrological, and suspended sediment data under several reservoir management alternatives [43]. As more information is obtained, the program models are continuously updated to closely approximate actual events. The Laterally Averaged Reservoir Model (LARM) is one such program which has been in use for many years and has been improved and now is called LARM2. By using these computer models and testing them against actual events, density currents can be predicted from information such as inflow volume, velocity, and density. In this way, optimum results can be obtained [44]. Other models are available which are neither as expensive or accurate as computer models. A mathematical model has been developed for predicting temperature and turbidity stratification dynamics for shallow reservoirs [45]. An heuristic model has even been developed whereby information generally true about a particular system or portion of a system may be used to model a system without any specific information [46]. Regardless of the modeling

method used, the purpose remains to reliably predict events and thereby increase control over a system through its optimum operation.

46. In any survey of water quality conditions, those involved must fully understand the testing methods and procedures before any data can be interpreted. A knowledge of the test's development and previous use also helps provide a basis for its application as a problem-solving tool. For this reason, some of the more important water-quality tests and particle-examination tests need to be reviewed.

Turbidity Assessment

47. The term turbidity refers to the degree to which water clarity is reduced by the presence of suspended matter. Only in the recent past did the measurement of turbidity gain full acceptance by the U. S. Environmental Protection Agency (EPA) as a means of determining water quality. This test was so long in being accepted because of the many variables that can interfere with a test based on optical measurements. Over the years, there was some disagreement as to what exactly was meant by the term turbidity. In the field of physical chemistry, turbidity is the measurement made of the intensity of unscattered light transmitted through the medium and nephelometry is the measurement of the intensity of the scattered light measured usually at a right angle to the light source. These various definitions continued to be confusing until "Standard Methods" clarified and seemed to combine them in the 1960s by defining turbidity as an expression of the optical property of a sample which causes the absorption and scattering of light rather than its transmission straight through the sample [47]. However, before this unification could come about, a number of different

turbidity units of measurement were established. Thankfully, some of these units are equivalents such as the Jackson turbidity units (JTU) which are equal to the Kieselgur units which equal the new nephelometric turbidity units (NTU) established by the E.P.A. In addition, there are the two formazin units, E.B.C. and A.S.B.C., the absolute units A.E. (Zeiss-Pulfrich turbidity unit), the Helm units, the Mastic units, and the Langrohr units [48].

48. The Jackson candle turbidimeter was widely used for many years to determine this water quality parameter. This simple instrument consists of a standard candle, glass tube, and metal stand. The turbidity of the sample was measured by filling the glass tube with the sample water until the light from the candle directly below could not be seen by looking down through the water sample. The mark on the calibrated glass tube to which the water level extended was then recorded as the turbidity. The Jackson turbidity unit was for many years considered to be the rough equivalent of suspended sediment measured in milligrams per liter [49]. This equivalent has been abandoned with the advent of nephelometric turbidity measurement. Since nephelometry depends on the characteristics of the suspended particles, the total number, size distribution and geometrical form of the suspended particles, the angle of scattering, and the spectral distribution of the incident radiation become the primary variables which determine this relationship [50].

49. Turbidity is the condition which results from the presence of suspended sediments. In many cases where turbidity is blamed for problems with fauna, it is only the symptom of the true problem which is suspended sediment. Some of the harmful effects of turbidity or

suspended sediment have already been mentioned. Other harmful effects have been well documented by studies conducted on salmon and trout streams such as the comparison of the total lack of success for trout eggs hatching in turbid waters versus 98% success in clear water [51]. The effects are not harmful, however, in all cases. A study of the responses of brook trout and creek chubs to turbidity discovered that both the trout and chubs were more active in the presence of moderate turbidity and while the trout showed no preference, the production of creek chubs was actually promoted by the presence of turbidity which aids in concealment from predators [52].

50. A definite relationship between turbidity and suspended sediments or suspended solids has been hard to establish. Here again, it is important to clarify what is meant by suspended solids. Suspended solids are the milligrams per liter of solids found suspended in the water to be sampled which are retained when the sample is passed through a glass fiber filter. (This is discussed further in the section on sampling methods.) Comparisons have also been attempted using particle counting methods to establish a relationship between turbidity and number of suspended particles. Most researchers and even the American Public Health Association have concluded that attempts to correlate turbidity with the weight concentration of suspended solids is impractical. In spite of this opinion, studies have shown that turbidity measurements may be used in estimating suspended sediment yields. A survey conducted on the Sleepers River in Vermont demonstrated that a reasonably consistent turbidity-sediment relationship existed and was more accurate at higher turbidities rather than the lower turbidities [53]. The reason that correlating turbidity and

suspended solids is thought to be impractical can be seen in the results of a study conducted on three Colorado streams. A high correlation was found to exist between turbidity readings and individual sediment types, but a poor relationship was found when the sediment type varied. This meant while a strong relationship could be established between turbidity and suspended solids for any one particular river or type of watershed area, the relationship would vary for each different system. Therefore, a universal relationship between turbidity and suspended solids could not be found which could be used for every stream or river [51].

51. Since the particle characteristics of size and shape as well as the reflection or absorption of specific spectral wavelengths have such an important effect on turbidity measurements, methods have been devised to overcome these characteristics. In an attempt to correlate turbidity measurements with suspended solids concentrations for a wastewater sample, a study was conducted which used a light source adjusted to near the infrared range to eliminate interferences due to sample color. The sample was also blended to produce particles of consistent size. The experimental data were plotted as percent transmittance versus mg/liter of suspended solids to obtain a calibration curve. This was then used to scale a colorimeter so that suspended solids could be read directly [54].

52. Another test that is often made on water samples containing suspended particles is to determine the sizes of the particles present. This size distribution of natural particles can often be simplified by representing the distribution as a lognormal function. Examples of lognormal particle-size distributions found in nature include the sand-size bed material of the Rio Grande and West Pakistan Canals [55].

If greater accuracy is desired, a number of methods have been used through the years to provide particle-size analysis. One of the early methods developed in the 1920s was the pipette method which involved timed withdrawals of the settled particles by pipette. Although this method provided good results, the sample was disturbed with each withdrawal and the withdrawn sediment had to be oven dried which delayed the results [56]. Another method which has been used to determine particle-size distribution is that of screens and filters. In a study conducted using marine particles, it was shown that screens began to retain particles having a size of about half of the mesh size and that 50% retention occurred for particle sizes at about the mesh size. It was also concluded that screens were more effective than filters [57]. From these results, this method appears to be too inaccurate for serious use. It should also be noted that a size distribution may be made on the basis of particle volume as in the pipette method, weight as in the filter and screen method, or particle diameter.

53. The hydrometer method of particle-size analysis is widely used in the soil sciences. A hydrometer is a weighted bulb with a calibrated stem which is placed in a water sample containing suspended particles. As the different size particles settle from suspension, a corresponding change in effective water density results and the height at which the bulb floats in the sample changes. By monitoring the level of the calibrated bulb stem over time, and plotting this against particle-size diameter, a particle-size distribution may be calculated. In this case, the particle-size diameters have been verified by the pipette method [58].

54. The accuracy of each of the methods mentioned thus far had to be checked against known conditions. For the most part, these conditions were determined by what is known as the microscopic method, which means that the sample was examined and the particles sized visually with the aid of a microscope. But even this method has problems since the removal and handling of the particle to be viewed may either change the shape or size of the particle or even create many small particles by fragmentation. The major problem with this method, however, is how time consuming it is. To overcome these problems, optical-sedimentation and direct optical methods have been developed [59]. An example is the SediGraph 5000 instrument which employs x-rays to determine the concentration of particles remaining at decreasing sedimentation depths as a function of time. This information is then applied against Stokes' law and a size distribution is developed [60]. Another example of this method is the hydrophotometer developed by Rice University. The theory is based on the relationship between changes in percent light transmission which is passed through a sediment suspension and differential particle settling as determined by Stokes' law. This method is classified as a photo-extinction method and was found to be four to five times more accurate than the conventional pipette method [56]. When only the average particle size is needed, a simple procedure has been developed which determines this value from measurement of the apparent specific turbidity of a sample [61].

55. The use of turbidity measurements in particle-size analysis probably reached a peak in 1963 when the Interagency Committee on Water Resources built a unique optical-sedimentation apparatus which used scattered light for size analysis. A recording turbidimeter measured

transmitted light for 15 seconds and the scattered light for 45 seconds after which the ratio was computed and recorded. The device was able to measure both concentration and particle-size distribution. Concentration was determined from the turbidity as the sample was continuously pumped through the detector. After the flow was stopped, turbidity was recorded against time for the sample in a sedimentation cell. Unfortunately, the turbidimeter-based device was unable to reproduce results among samples of differing compositions, and production of the units ceased.

56. Most of these methods have estimated the actual number of particles of a particular size range which are present in a sample. A few have actually counted each particle, as in the microscopic method. There are now two methods available which can both count the particles present in a sample and provide a size analysis.

57. The Coulter counter was originally developed for the rapid, routine counting of blood cells but has since been modified to be of use in many other applications. The instrument operates on the principle that when a particle suspended in an electrolyte passes through an electrical field, it will cause a change in the field if the electrical properties of the particle differ from those of the electrolyte. The change produced is proportional to the volume of electrolyte which is displaced by the particle's volume. There are two limitations to the use of the Coulter counter. The first is that the particles being examined must have a different resistivity than that of the electrolyte. The second is that the sample must be diluted so that only one particle may pass through the electrical field at a time [59].

58. The second method available today for particle-size analysis and counting utilizes an automatic size analyzer and plotter manufactured by the HIAC Instruments Division of Pacific Scientific. This instrument operates on the principle of light blockage for counting and sizing particles. A beam of light is directed across the sample flow at a very small constriction. When a particle passes through the opening, a reduction in the amount of light reaching a photodetector on the other side of the constriction is produced. The resulting voltage pulse from the photodetector is proportional to the size of the blocking particle. The particle size is then recorded as the diameter of a circle having an equivalent area [62]. The HIAC machine has been able to avoid the limitations which apply to the Coulter counter since no electrolyte is required. Turbid waters may require dilution but most samples can be examined quickly and directly with the aid of the system's microprocessor.

59. Although the HIAC system is relatively new, it has been employed over a wide range of applications in the field of water treatment. A study of algae and bacteria populations within Garvey Reservoir in Los Angeles, California, used the instrument to establish an association between bacteria and green algae. It was also determined that turbidity in the reservoir was closely associated with particles sized between 2-40 μm . By correlating particle size to the size of bacteria, the HIAC instrument proved useful as a water quality management tool [63]. The instrument has also been used in pilot plant process evaluation and optimization. By use of particle counts throughout the treatment process, the maximum particle removal and optimum treatment economy can be attained [64]. Treatment of water plant sludges has also

been refined with the aid of the HIAC system in a study conducted in water treatment facilities in Virginia. The dewatering characteristics of the sludges were examined and found to be primarily dependent on the size distribution and shape of the floc particles [65].

60. Comparisons between particle counts and turbidity have also been attempted. Generally, the trends produced by the two tests are similar but a good point-for-point correlation does not exist [62]. In cases where the turbidity-causing particles are of the same material and fairly uniform in size, a linear relationship was found to exist. Linear relationships having different slopes resulted, however, when particles of different materials were sampled. Even so, this does allow simulations to be made and the terms exchanged once a linear relationship is developed for a particular water [50].

61. The use of electrophoretic mobility measurement was first introduced in 1928 but was rarely used by either the water industry or coagulation research until the late 1950s. Since that time, the measurement of electrophoretic mobility or zeta potential has been developed as an indicator of the optimum coagulant dosage required for the coagulation process in water treatment [66]. Measurement of particle charge in nature has concentrated primarily on the mixing which occurs in estuaries. One such study conducted in four separate estuaries within the United Kingdom found the charge distribution of all the samples taken to be highly uniform despite the mixed condition of the suspended particles. This result is important because it indicates that the control of particulate surface properties is dominated by adsorbed organic matter or metallic oxides. The composition of the

particles and their origin had very little influence on their final surface charge [67].

62. Tests which examine the composition of the particles include the use of x-rays to determine the type of clays which might be present and the oxidation of the volatile portion of sediments to provide a rough measure of the particle's organic content. The field of x-ray analysis has been improved to where the clay mineral species can now be identified on a particle-by-particle basis without causing changes in their structural form or association. This improvement over the standard x-ray diffraction methods was made possible by the advent of high-resolution scanning electron microscopes coupled with energy-dispersive x-ray analyzers [68]. The use of high test heat to oxidize the volatile portion of sediments has been available for many years. Only recently, however, was this measurement considered to be a rough equivalent of the sediment's organic content. One study which made use of this equivalent was able to track changes in the organic content of suspended sediments along the length of an estuary [69].

Summary

63. The testing methods to be employed in this survey were chosen on the basis of their estimated importance. In determining if a test method would be of aid in understanding the situation at Lake Cumberland, the review of the literature provided a great deal of guidance.

64. The causes of particle suspension or slow settling found in the literature were centered around the size and charge characteristics of the particles examined. To determine if the suspension or slow

settling exhibited is due to the charge or to the size of the particles, a size distribution test as well as a test of the zeta potential was required. The literature suggested that the suspended particles such as those found in Lake Cumberland tended to be clay mineral particles. In cases where the particles were not clays, the volatile suspended solids test was utilized to estimate the organic content of the suspended sediment. This classification process would begin with x-ray diffraction to identify any clay minerals present and would be followed, if necessary, by a test for volatile suspended solids. The results of these three or possibly four tests would determine: (1) the size range of the particles which appear to be suspended; (2) whether suspension occurs as a result of particle charge; (3) the type of clays which are present in the suspended sediment or the organic content of the suspended sediment if no clays were found.

65. The literature demonstrated that turbidity layers operate as a density flow, usually on the basis of temperature stratification. In order to locate, track, and measure the intensity of the turbid layer, turbidity samples were to be taken and tested. Measurement of temperature with depth was also required to identify the temperature gradient of the water body. A comparison of these turbidity and temperature measurements taken over a period of time would display any settling on the part of the particles comprising the plume. By measuring the turbidity and temperature over a period of time, the movement of turbidity through the lake can be tracked. This information will also clearly establish whether the particles are stably suspended or undergoing slow settling.

66. Although not required for a determination of the situation at Lake Cumberland, comparisons of the turbidity measurements with the suspended solids and the number of particles present were also desired in order to evaluate the test methods themselves. This necessitated testing for suspended solids on each sample taken from the lake. The results of these proposed tests should provide sufficient information to explain the dynamics of suspended sediment transport within Lake Cumberland as well as to characterize the sediment particles.

PART III: METHODS AND MATERIALS

67. As was previously mentioned in the introductory section, this project consisted of six data collection trips to Lake Cumberland, Kentucky, between March and September, 1983. These trips were conducted approximately a month apart near the twentieth day of each month. Originally it was planned that the equipment used in measuring turbidity, number and size distribution of particles, and particle charge could be moved daily from hotel to hotel as the sampling stations were completed along the length of the lake. The initial trip, conducted from 21 to 23 March, exposed this method to be unrealistic due, in part, to the volume of equipment which would require moving, but primarily because of the fragile nature of some of the electronic components. This resulted in increased time and travel costs due to the commuting distances between the various sampling stations and the equipment located at Lake Cumberland State Park. During the five subsequent trips, Monticello, Kentucky, was utilized as a more central location for this equipment.

68. The six sampling points within the lake were located at the dam (river mile 461.4), below the Fall Creek boat ramp (river mile 487.0), above the inflow of Fishing Creek (river mile 509.3), above Burnside, Kentucky (river mile 519.0), above the inflow of Buck Creek (river mile 534.8), and south of General Burnside Island State Park (Big South Fork Cumberland river mile 2.3). The seventh sampling point, as noted previously, was located immediately downstream of Wolf Creek Dam (river mile 460.4).

Data Collection

69. The data collected from each trip were actually the product of three distinct segments of the trip. As explained in the scope of the work, the water temperature, dissolved oxygen content, pH, conductivity, and oxidation-reduction potential were measured while at the sampling site. These measurements were taken at ten-foot intervals from the surface to within a few feet of the lake bottom at the deepest point of the cross section at each station. This segment of data collection will be referred to as in situ measurements.

70. Although the turbidity was spot checked while at the sampling stations, most turbidity measurements had to be conducted at Monticello. This was due to the condensation produced on the glass test cylinder when filled with the cool subsurface water samples. In addition to the turbidity measurement, the number of particles per milliliter and their size distribution along with their average electrical charge was measured. These measurements were made during the date of collection from bottled samples taken at twenty-foot intervals from the surface. This segment of data collection will be referred to as same day measurements. These same bottled samples were returned to the laboratory at Tennessee Technological University where each was tested to determine the total solids content and suspended solids content. From this information, the dissolved solids content was then calculated. These measurements comprised the final segment of data collection which will be referred to as laboratory measurements.

In Situ Measurements

71. The equipment required for obtaining this portion of the data might be considered of special interest to others involved in future projects of this type. The boat which served as the sampling platform was a commercial lightweight aluminum fishing boat approximately 14 feet long and five feet wide. A Johnson 35-horsepower outboard motor provided the necessary propulsion. The only major alterations were the addition of a boom mount for a four-foot high, three-foot long arm boom and a wench containing approximately 220 feet of one-eighth inch steel cable. The boom was constructed of 1½-inch galvanized steel pipe with a welded loop at the boom's end for connecting a pulley through which the steel cable would run. The cable itself had been painted using color-coded rings to represent the depth to which the attached device was lowered. The boat was also equipped with a Hummingbird WPD 60 depthfinder. This was employed in determining the deepest point in the lake's cross section at each station. The depthfinder was also useful in checking instrument and anchor depths.

72. The primary instrument used for obtaining measurements at each station was the Hydrolab Surveyor model 6D. This instrument consists of a surface unit, a connecting cable, and a submersible cylindrical housing containing the water-testing probes. The surface unit is a water-tight panel meter with operating controls for measuring the signals being returned by each of the various submerged probes. The connecting cable provides power to the probes and returns their signals to the surface unit. The depth to which measurements can be made depends on the length of supporting steel cable or the length of connecting cable available. For this project, the length of connecting

cable limited the depth to which measurements could be made to 160 feet with a 165-foot connecting cable. The cylindrical housing includes an electric motor-driven sample circulator which provides a continuous flow of ambient water sample across the probes. The probes allow for the measurement of dissolved oxygen content, pH, conductivity, temperature, and oxidation-reduction potential. These values can be read directly from the various scales located on the panel meter by adjusting the controls to each parameter. The power used to operate the circulator and probes is provided by a small 12-volt D.C. battery connected to the surface unit within the boat.

73. The accuracy of the Hydrolab probes are $\pm 0.2^{\circ}\text{C}$ for temperature; ± 1.0 percent of range used for conductivity; ± 0.1 standard unit for pH; ± 0.2 mg/l for dissolved oxygen and ± 20 mV for the ORP probe.

74. The submerged probe housing also serves an important function in obtaining water samples at the different depths. To accomplish this, three pieces of equipment are necessary--a hose, a pump, and a heavy-duty battery. The intake of the hose was attached to the probe housing with slotted metal band radiator hose clamps. Two 100-foot lengths of heavy-duty commercial 3/4-inch garden hose were used to transport the water sample from the probe's depth to the surface. A Teel model 1P580B self-priming marine utility pump was used to pump the sample through the 200-foot length and discharge the flow from a shorter length of hose connected to the outflow side of the pump. The water from the pump was released on the opposite side of the boat from the lowered hose. The small Teel pump was powered by a heavy-duty marine 12-volt D.C. battery.

75. Water samples were taken from the pumped flow at 20-foot intervals from the surface. The Hydrolab was first lowered to the lowest measuring depth and then raised in ten-foot increments. At the 20-foot intervals, the Hydrolab values were recorded and then the water samples taken. This was to insure that the water from that depth had been given enough time to be pumped through the 200-foot length of the hose. The water samples were caught and stored in numbered Nalgene 300-ml plastic bottles. These bottles were thoroughly washed and then rinsed with distilled water before each sampling trip. When the actual sample was being taken, each bottle was repeatedly rinsed in the pumped flow prior to collecting that sample. The samples and Hydrolab values for the surface were actually taken about six inches deep to prevent interference from the water which had already been pumped up to the surface.

76. This continuous flow of ambient water was also used in spot checking the turbidity changes with depth. The Hach Portalab turbidimeter was carried aboard the boat in order to find the depth having the greatest turbidity so that a larger sample from that depth could be taken. For these larger samples, gallon Nalgene jugs were used.

Same-Day Measurements

77. This segment of data collection included the measurement of turbidity, particle number and size distribution, and particle electrical charge or zeta potential. These measurements were made using the water samples taken at the twenty-foot intervals. Although these measurements have the disadvantage of being made on samples no longer at

their original temperature or pressure, the delay was necessary in order to have a common basis for comparison, especially in regard to temperature. All of the samples collected during each day were allowed to reach room temperature before being examined. Prior to testing, each sample was shaken vigorously so that any particles which might have settled would be resuspended to represent the sample's original composition.

78. The turbidity measurements were made using a Hach Portolab turbidimeter model 16800 which measures in nephelometric turbidity units (NTU's). The meter is simple to operate and is powered by self-contained nickel-cadmium batteries. Sample turbidity is displayed using one of three scale ranges: 0-1, 1-10, and 10-100 NTU. Accuracy of the instrument is 2 percent of the scale readings.

79. Measurement of the number of particles and their size distribution was provided by a HIAC model PA-520 Particle Size Analyzer and plotter. The particle size analyzer consists of a vacuum pump, particle sensor, microprocessor, and plotter. The particle sensor operates using the HIAC principle of light blockage. The sample is directed at a constant rate through a rectangular passage which is uniformly illuminated from a window at one side of the passageway. When a particle is present, the light passes through the sample and impinges on a photo-electric detector which generates an impulse whose amplitude is proportional to the amount of light which is not received by the detector. This difference in light generated versus received is correlated to pulse values for particles of known cross-sectional area by the microprocessor which counts the particle and stores the area information for computing size distribution. The size range of

particles which can be measured depends upon the dimensions of the sensor's rectangular passageway. By changing the sensor, a different size range of particles can be examined. During the March data collection trip, a sensor for particles ranging from 10 to 450 micrometers was used. For the remaining five trips, the sensor used measured particles ranging in size from 1 to 45 micrometers. This was changed in order to examine the smaller-sized particles typical of clays and silts. The analyzer was calibrated by the factory on April 4, 1982, and had an accuracy in terms of size of about ± 5 percent. Our experience on numbers of particles using duplicate runs was $\pm 10\%$.

80. The sample is examined by placing it in a beaker along with a magnetic stirring bar. The beaker is then placed on the surface of a stirrer which can be raised to become flush with a pressure cylinder. The use of the magnetic stirrer aids in retaining particles in suspension after the sample is vigorously shaken in the collection bottle. A metal tube extending into the sample is then used to transport the liquid through the particle sensor at a constant rate under pressure. After a specified volume of sample has flowed through the sensor, the microprocessor initiates the plotter which graphs the stored data. A sample volume of 10 ml was chosen for testing in this project. The test volume could be adjusted by moving light-sensing rings located on a graduated glass sample tube.

81. The particle-size distribution information stored by the microprocessor could be plotted in a variety of ways. The information could be plotted as the percent of total number of particles greater or smaller than a stated size, the percent of the total volume of particles greater or smaller than a stated size, or the percent of total number or

volume of particles equal to a stated size (size distribution). For each sample collected during this project, a percent of the total number of particles less than curve was plotted along with a size distribution curve for the total number of particles. The plotter, which is manufactured by Esterline Angus Instrument Corporation, is a flat-bed type plotter with a sliding pen arm. By the electro-mechanical positioning of the pen and arm, the plotter is able to simultaneously measure and record the information for two independent variables being provided by the microprocessor. The positioning of the calibrated graph paper is determined by lighted slots in the surface of the plotter which, along with other small openings, help maintain the paper's position by vacuum pressure.

82. The average electrical charge on the particles of a sample was also measured during the day of collection. This electrical charge on a particle is also known as the particle's zeta potential. The zeta potential of each sample was measured by use of a model ZM-80 Zeta-Meter. The zeta-meter uses a procedure called microelectrophoresis where a D.C. voltage is applied across a cell containing the sample to be examined. Because the particles are electrically charged, they are attracted to and move toward the oppositely charged electrode. The velocity at which a particle moves is proportional to the charge or zeta potential of the particle. Particles exhibiting strong charges are considered to be more stable in suspension. A number of particles, usually ten, were tracked and the average particle velocity was then related to a zeta potential value by means of a nomograph.

83. The zeta-meter consists of a power unit and microscope module. The power unit controls the voltage applied to the sample and

contains a timer for recording particle velocity over a specific distance. The microscope module consists of a microscope for particle tracking with one eyepiece containing a tracking grid, and a sample cell with electrode connections at each end. The cell is illuminated by two lamps mounted on the module's base. The accuracy of the Zeta-Meter is dependent upon dilutions, operator judgment, timing, and the scale on the Z-M nomograph. The manual does not give an accuracy figure.

84. After the testing of each separate sample, the volume of sample not pumped through the sensor of the particle size analyzer and the portion of sample placed in the electrophoresis cell of the zeta-meter were returned to the sample bottle. This was done in order to retain the maximum amount of sample possible for the testing to be carried out at the laboratory.

Laboratory Measurements

85. The final segment of data collection from each of the six trips occurred at the Civil Engineering laboratory facilities of Tennessee Technological University. These tests, conducted within the first few weeks after each trip, measured the total and suspended solids content of the bottled samples. The testing methods used were in accordance with the methods outlined in Standard Methods for the Examination of Water and Wastewater for total and total filterable residue dried at 103° to 105°C. In both tests, the dishes and crucibles used were heated to 600°C or greater for an hour or longer. After cooling, they were numbered and transferred to a desiccator ready for use.

86. The test for total solids consisted of placing a known volume of sample into its corresponding pre-weighed evaporating dish. If available, a volume of 100 ml was normally used in this test. The evaporating dish was then placed in a drying oven overnight at approximately 98°C. This temperature was used to prevent boiling and loss of sample by splattering. After the sample reached dryness, the temperature was elevated to 103° to 105°C for at least one hour. The numbered dishes were then placed in desiccators to cool and then a final weight was obtained. The difference between the initial weight and the final weight was determined representing the total solids content in 100 ml of sample. This value was multiplied by a factor of ten to obtain the total solids in terms of milligrams per liter of sample.

87. The suspended solids content of each sample was also determined. Preheated Gooch crucibles were placed on a vacuum apparatus and glass-fiber filters fitted over the porous bottom of each with the aid of distilled water. The combination of crucible and filter was then dried in a drying oven at 103° to 105°C for over an hour. The crucibles were allowed to cool in desiccators and then weighed immediately before use. A volume of 100 ml from each sample was then passed through its corresponding crucible and the crucible and filter combination dried again as before. After cooling in a desiccator, the crucibles were again weighed. The difference between the initial and final weight was multiplied by a factor of ten to represent the total suspended solids which would be found in a liter of that sample. Accuracy is reported to be associated with unknown factors, but precision varies from 1 to 10 percent depending upon concentration.

88. After the results of these two tests were available, the difference between the total solids and total suspended solids was determined for each sample. This difference represents the portion of the total solids which were dissolved.

Particle Characterization Tests

89. The tests conducted during the six surveys provided information concerning the water conditions and the number, size, and charge of suspended particles. These tests did not provide any information on the actual composition of the particles present, however. The x-ray diffraction and volatile suspended solids tests were conducted on the suspended sediment found in the large samples taken from the turbid layer. A set of prepared samples was also tested as an experimental control.

X-ray Diffraction

90. The x-ray diffraction test was carried out in an attempt to determine the mineral content of the particles which were remaining suspended. If this information could have been obtained, it might have been possible to determine the tributary or perhaps the specific geographic area from which the particles originated. With the source located, a plan could then be formulated to reduce or prevent the release of this type of mineral particulates into the lake.

91. X-ray diffraction utilizes x-rays emitted at an angled sample to measure the spacings in the crystalline structure of the minerals present. As previously mentioned, the turbidimeter was used to

locate the highest turbidity depths where large water samples were taken. These samples were returned to the laboratory and evaporated down to a small concentrated volume. This was done by placing the numbered samples into correspondingly numbered beakers and evaporating in a drying oven at approximately 65°C. The combination of stillness, heat, and high concentrations caused the suspended particles to settle to the bottom of the beakers. A pipette was then used to transfer this sediment to numbered microscope slides where it was allowed to dry. A numbered slide from each sample was then inserted into the x-ray diffraction unit which slowly tilted the slide from 2° to 40°. The results for each slide tested were graphed on a moving bed recorder as the angle of the slides were slowly increased. The angles at which peaks occurred on the graph were then converted to their equivalent spacings between mineral layers in Ångströms. By comparison with spacings of known minerals, the mineral contents of the samples could be identified. Because many common peaks exist between different minerals, the x-ray diffraction test was performed three times for each sample. The first test was made using the unaltered dry slide as described above. For the second and third tests, the slide was moistened with ethylene glycol, tested, and then heated to 375°C for thirty minutes and tested again. This progressive testing eliminates various common peaks for different minerals and allows for more exact identification.

Volatile Suspended Solids

92. To supplement the x-ray diffraction test, the remaining portions of sediment from the evaporated water samples were tested to determine the percent of the sediment made up by organic matter. This

was accomplished by following the procedure found in Standard Methods for the Examination of Water and Wastewater to determine the volatile and fixed suspended matter. The samples were placed in numbered disposable, preweighed aluminum drying trays. The initial weight was determined after any moisture was driven off by heating at approximately 103°C for an hour and after the samples were allowed to cool in a desiccator. This was followed by heating to approximately 600°C for one hour and again weighing after cooling. The percent of volatile or organic matter present was then determined by dividing the change in sample weight by the original sample weight multiplied by 100. Accuracy is similar to those for total and suspended solids reported earlier.

Testing Controls

93. In order to estimate the reliability and consistency of the tests conducted on the raw water samples, a group of prepared samples were also tested. Prior to the sixth data-collection trip, a series of six control water samples were prepared in the laboratory. These control samples were produced by dilution of a 50 mg/l bentonite solution. The original and dilutions were made with distilled water and ranged from 9.375 mg/l to the full strength 50 mg/l solution. After completion of the first day's sampling, the six control samples were analyzed along with the samples collected that day for turbidity, zeta potential, the number of particles per milliliter, and their size distribution. The laboratory measurements of total and suspended solids were carried out at the completion of the trip followed by an x-ray diffraction analysis of a prepared bentonite sediment slide.

PART IV: PRESENTATION AND DISCUSSION OF RESULTS

94. Over the course of this project, a wide variety of tests were conducted on both the water within the lake and the particles found in water samples taken from Lake Cumberland. The results of these tests are presented and discussed in the following section. In addition to this, the results of two or more tests have been compared or additional data computed from the results in order to gain further insight into the dynamics of the system.

Water Quality Results

95. After collection, the data were processed and plotted by computer. Plots were made each month for the results of the water quality tests of conductivity; oxidation-reduction potential; pH; temperature; turbidity; dissolved oxygen; and total, dissolved, and suspended solids.

96. The results of some of these tests were determined to be of lesser value in observing the dynamics of the turbidity system although they did show typical lake phenomena common to stratified lakes in the temperate zone. Specific conductance, or conductivity, plots had little correlation with other test results and were of no aid in determining any type of consistent turbidity behavior on the part of the lake. The plots or charts of pH, dissolved oxygen, oxidation-reduction potential, and temperature results demonstrated an interrelationship between these measurements occurring in the months of strong stratification.

These relationships became noticeable in the June results and became stronger during the months of July and August.

97. A comparison of the results for these four tests shows that a drop in pH occurred below the thermocline until near the bottom of the lake where the pH began to rise slightly. Above the thermocline, the water was slightly basic and well-oxygenated. The high oxygen content resulted from photosynthesis carried out by the algae which lie within the epilimnion and thermocline region. The higher pH values found in the epilimnion were also due to the algae which utilize CO_2 in the photosynthetic process. This uptake of CO_2 acts to reduce the acidity and raise the pH of the surrounding water. The drop in pH below the thermocline corresponded to a drop in dissolved oxygen occurring in the same region. This is thought to be due to the biodegradation taking place as the algal organisms die and settle to lower depths. The slight increases in pH which were found near the lake bottom were probably due to the removal of carbon dioxide by benthic organisms which utilize inorganic carbon in the synthesis of cell material. The oxidation-reduction potential (ORP) was seen to correspond inversely with pH values. The higher ORP measurements occurred in the presence of the lower pH ranges and low ORP values were found in conjunction with high pH ranges.

98. The results of the tests for dissolved and total solids were also of little appreciable help in explaining the behavior of the lake. A very strong relationship between these two measurements was demonstrated by the plotted results but this would be expected since the dissolved solids measurement is a portion of the total solids present. Throughout the project, the total solids were composed primarily and

almost exclusively of solids in the dissolved state. Only after storm events did suspended solids become a significant constituent of the total solids measurement.

99. The plotted results for the tests of dissolved and total solids have not been included since they were of very little value in demonstrating the dynamics of the lake system. The two remaining water quality tests, turbidity and suspended solids, proved to be valuable tools in understanding the dynamics of both the lake and its suspended sediments. Therefore, the results of these tests are presented and discussed in greater detail on the following pages.

Turbidity

100. The turbidity charts for the six survey trips presented in Figures 7 through 12 clearly demonstrate the seasonal and storm-related incidence of turbidity. The turbidity during March was fairly uniform over the length of the lake and was primarily between 10 and 20 NTU's. Between the March and April surveys, the weighted rainfall for the Lake Cumberland area was 5.54 inches. The runoff from this rainfall produced net inflows up to 49,723 dsf (day-second-feet) and resulted in headwater elevation increases of 12.91 feet. The upper end of the lake became highly turbid as shown by Figure 8. Runoff was fairly intense during the period from April 5 to April 24. The monitor at Cumberland Falls was inoperable during this period but the monitor at Stearns on the South Fork showed incoming turbidities peaking at 120 during this period.

101. The April runoff was followed by a larger storm in May which raised the level of the lake significantly and produced a huge

influx of turbid water. Between the April and May surveys, the weighted rainfall for the Lake Cumberland drainage area was 8.08 inches. Most of this came in a continuous event extending from May 13 to 24 when 5.57 inches of rainfall occurred. Daily inflows from this rainfall ranged from 26,687 to 90,167 dsf and produced a rise in lake level of 14.31 feet. The overall rise in the lake level between the April and May surveys was 28.47 feet. The Cumberland Falls monitor remained inoperative but the Stearns monitor recorded turbidities up to 750 on May 22. Other high turbidities were recorded at 150 on May 3, 270 on May 4, 120 on May 5, 210 on May 9, 130 on May 15, 190 on May 16, 400 on May 20, 230 on May 21, 340 on May 23, and 170 on May 24. The resultant effect on turbidity in Lake Cumberland is shown by Figure 9. An influx of high turbidity water is certainly apparent.

102. In comparing Figures 8 and 9 for April and May, two important points should be noted. First, even though a month had elapsed, the influx of turbid water had not progressed to the dam. In fact, the inflow of turbid water had moved much like plug flow with the 10 NTU isoline or isogram progressing approximately 13 miles downstream. This slow progress was due to the resistance of the previously impounded water to mixing. The large inflow seemed to compress the turbidity isograms to the extent that by May the 50 NTU turbidity generated by the original storm appeared to have moved approximately 32 miles. Instead, what occurred was the fresh inflow of highly turbid waters which were able to mix with the previous runoff. This mixing increased the turbidity values over the length of the lake receiving major inflow from the tributaries. This indicated that when the lake is not stratified, inflows tend to act as plug flows. Second, the turbidity values over

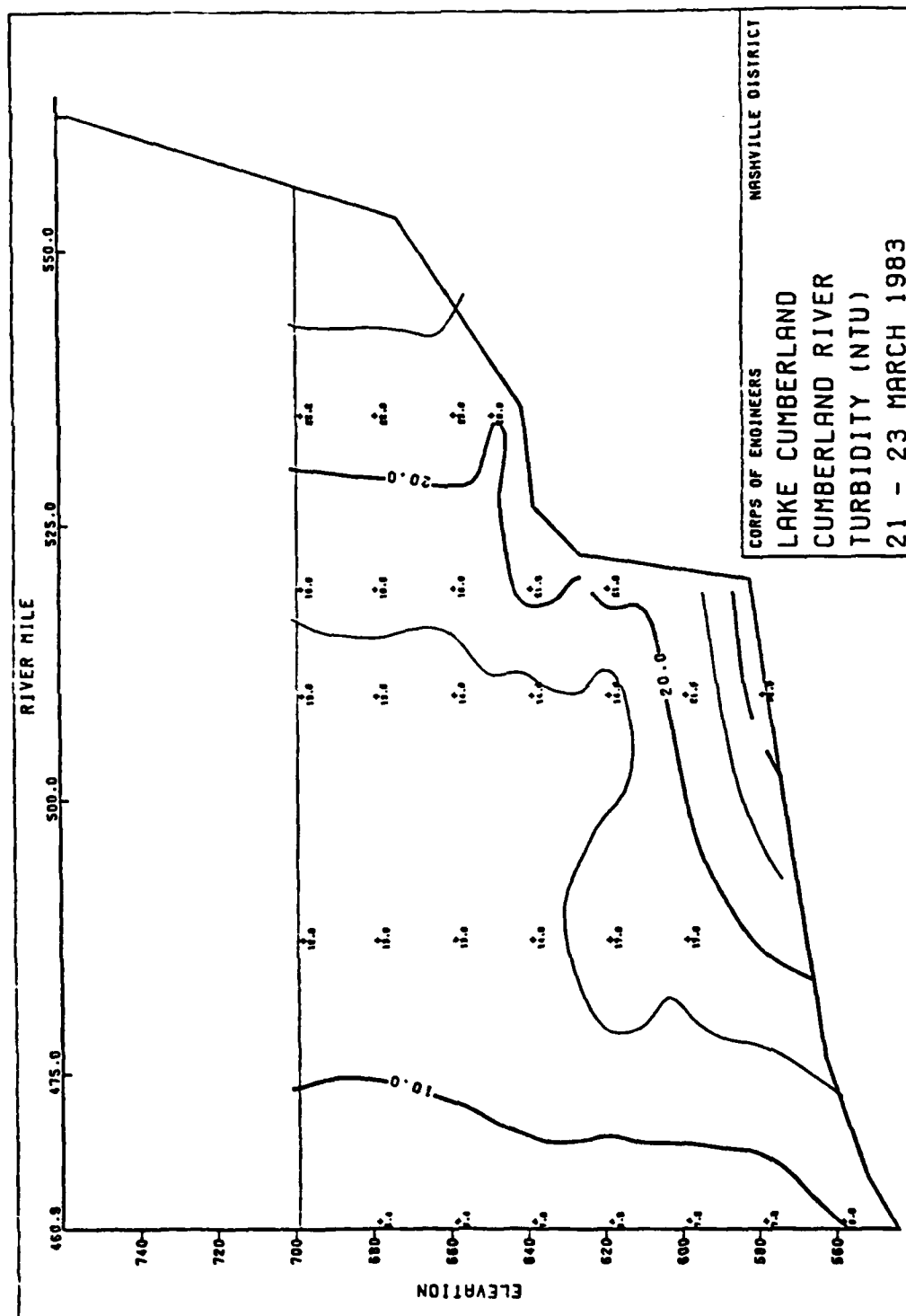


Figure 7. Turbidity Results of the March Survey

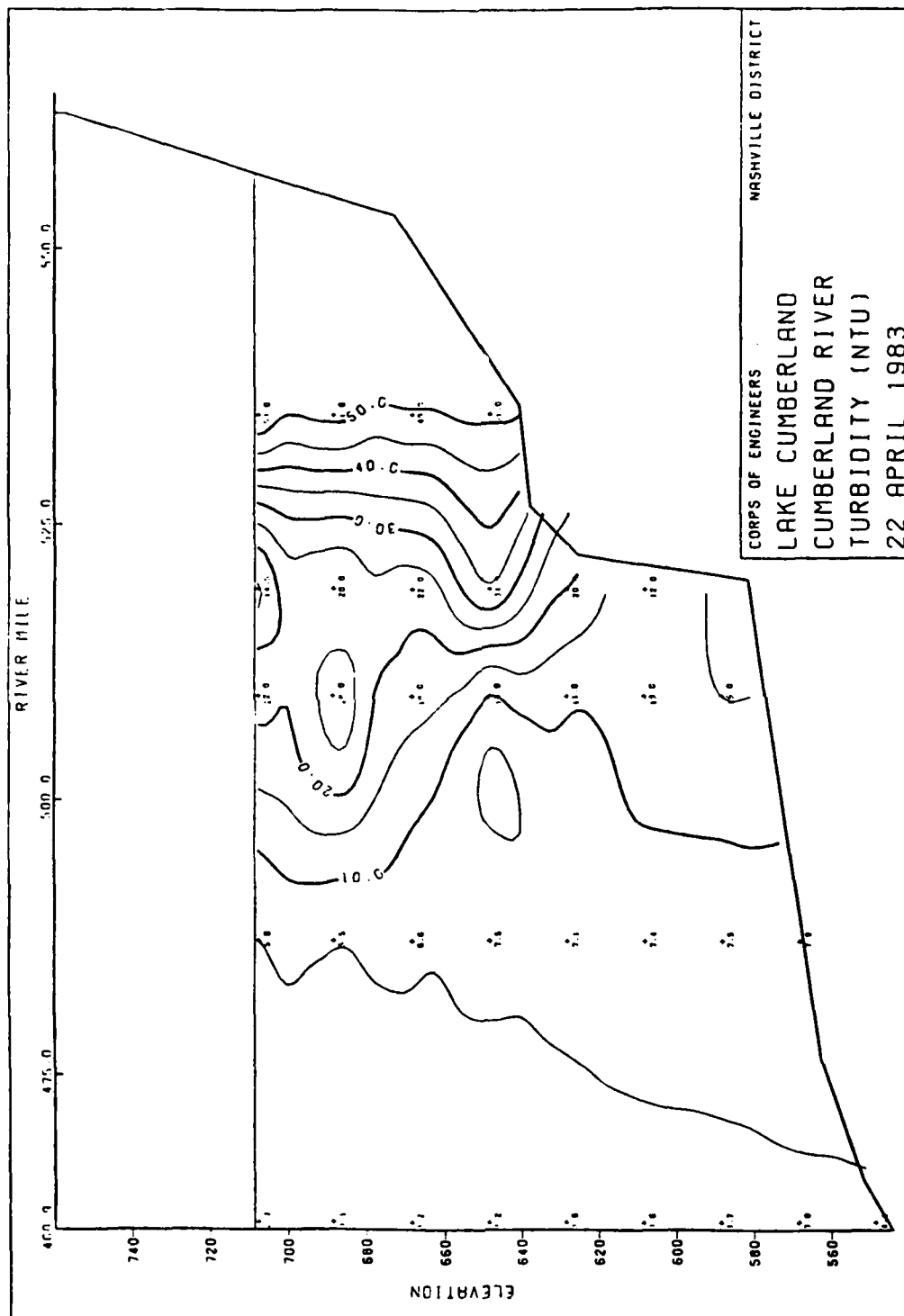


Figure 8. Turbidity Results of the April Survey

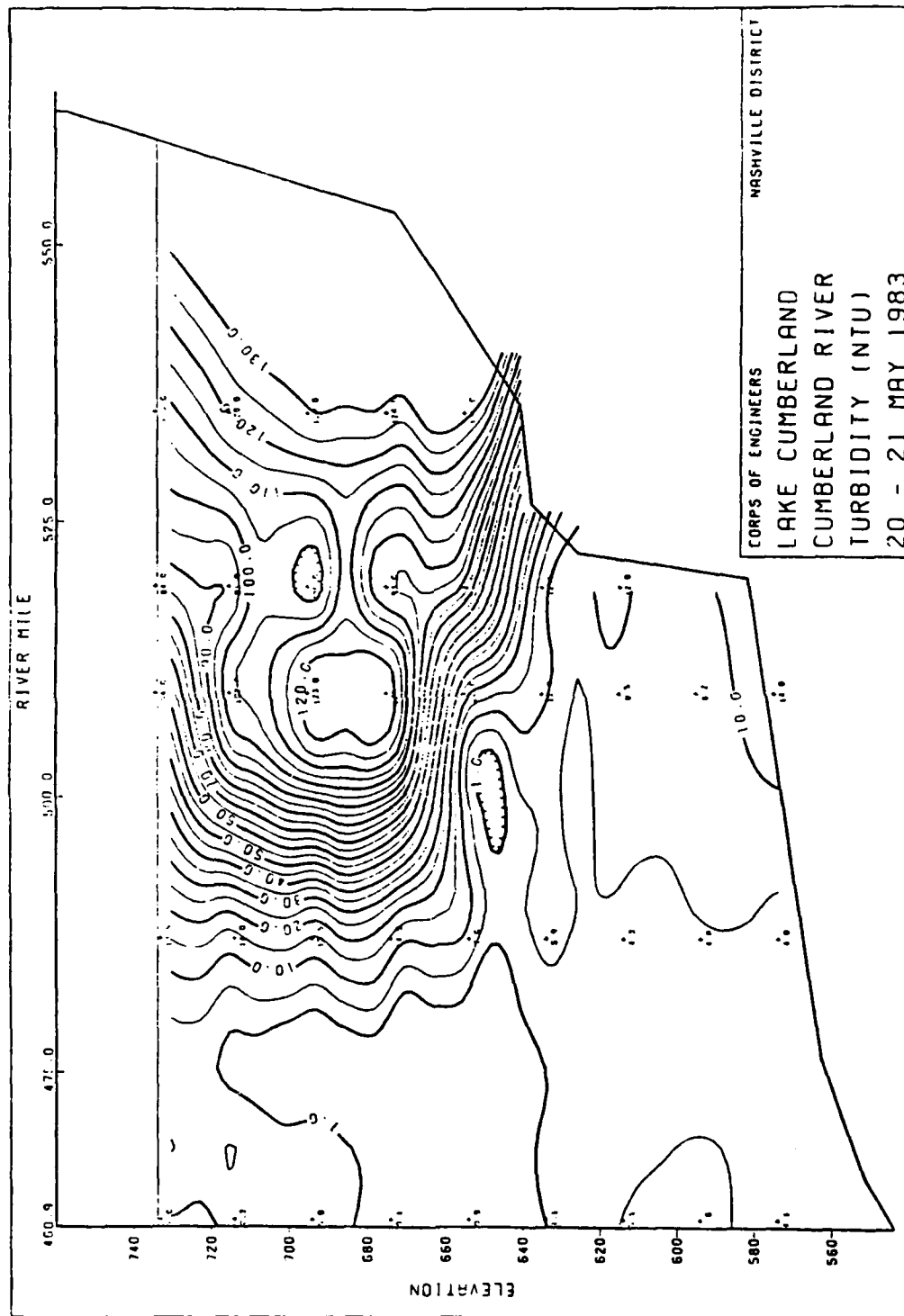


Figure 9. Turbidity Results of the May Survey

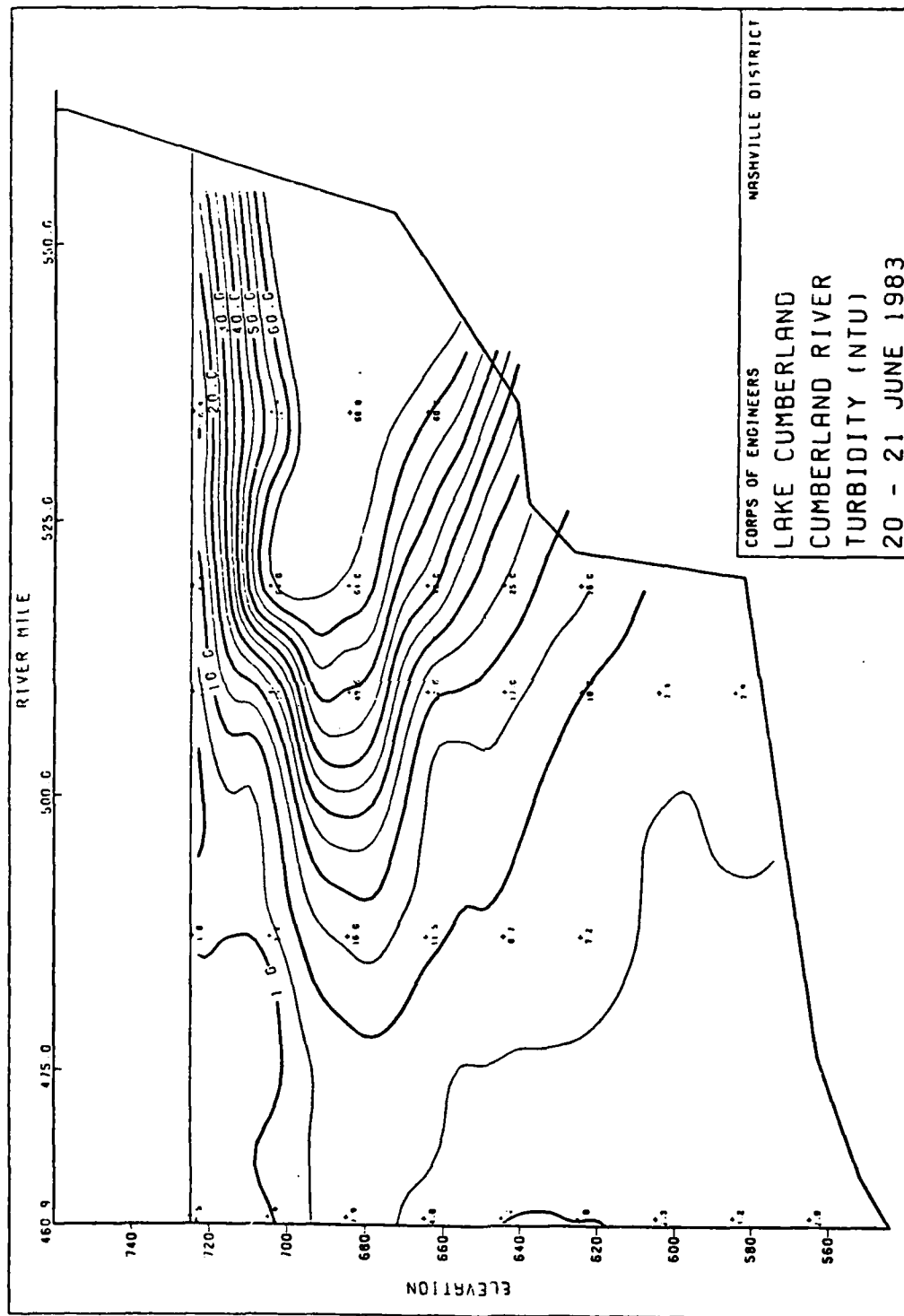


Figure 10. Turbidity Results of the June Survey

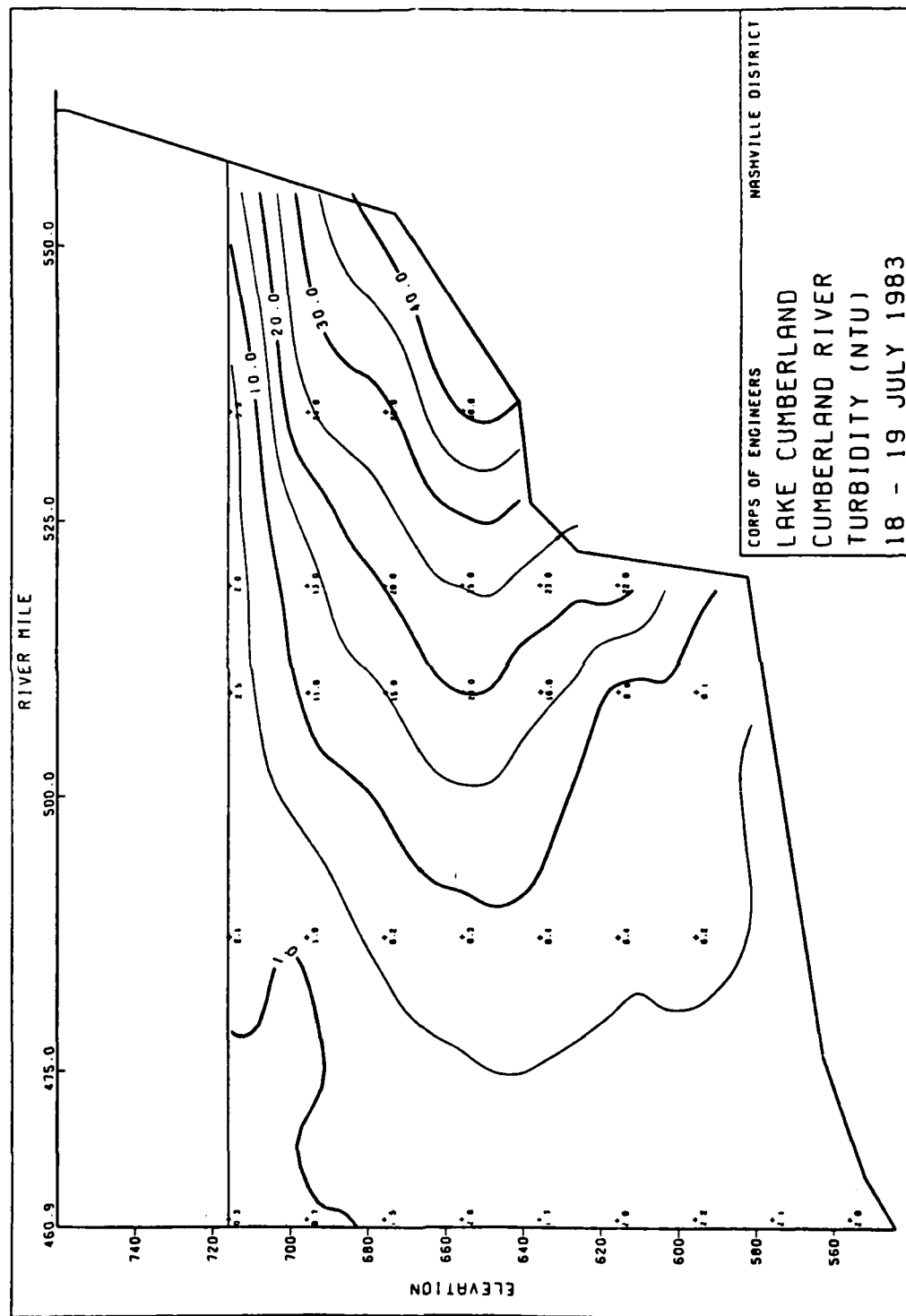


Figure 11. Turbidity Results of the July Survey

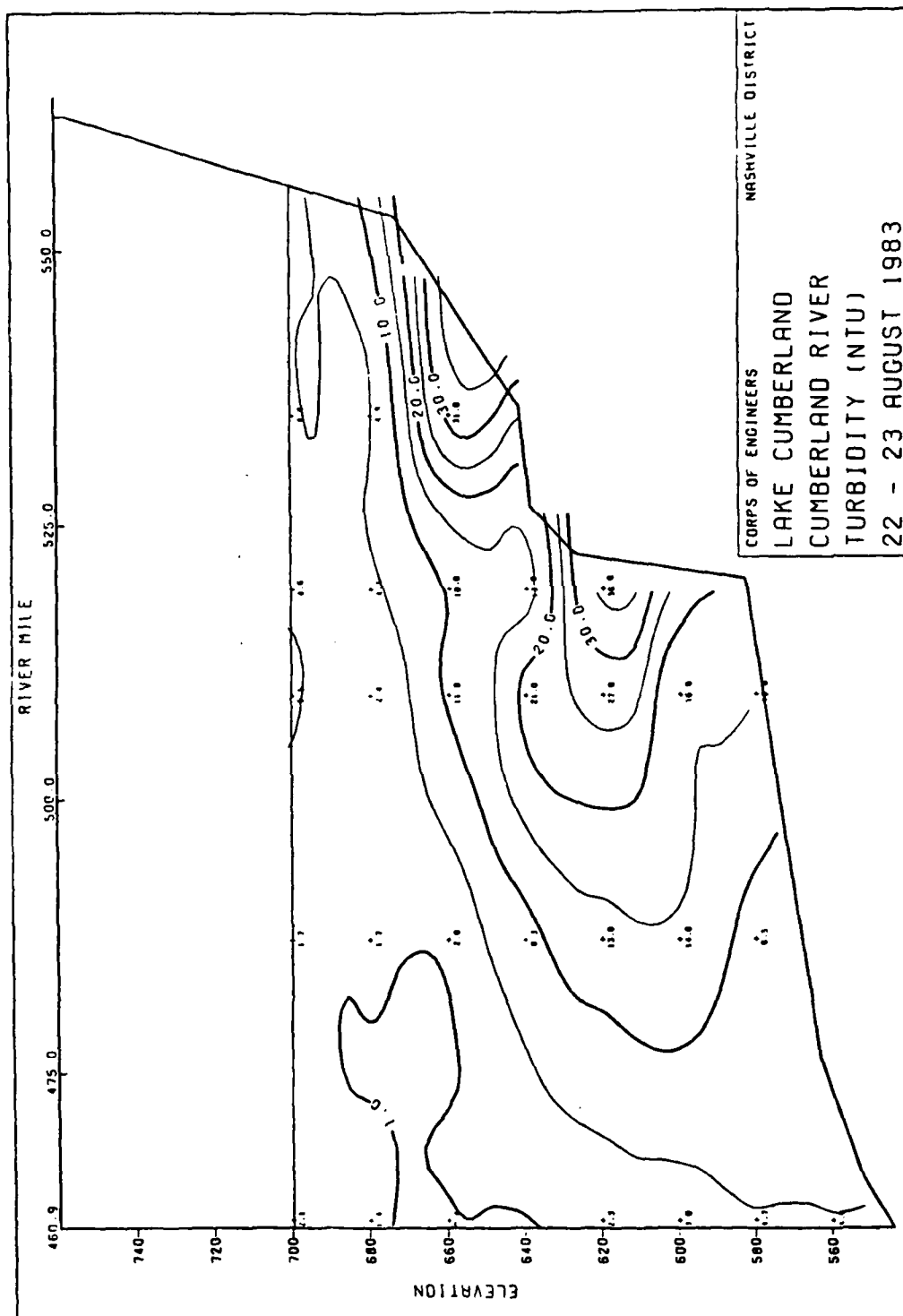


Figure 12. Turbidity Results of the August Survey

the lower third of the lake not only did not increase but usually decreased, in spite of the storm events which caused runoff over the entire shoreline. This indicates that the turbidity within the lake is almost exclusively the result of inflow from the major tributaries and not the result of local runoff.

103. With the onset of stratification during June, the turbid waters began to act as a density interflow which moved slowly toward the dam during the next two months. It should be noted that over the period of May, June, and July, there was a decreasing loss of turbidity with a large amount removed by June and a smaller additional amount lost by July. This corresponded to the loss of material which was settling out with settling velocities proportionate to their size and weight. This proportionate settling can be seen as the cause of the increased thickness of the turbidity layer shown in Figures 10 and 11 from June to July.

104. Figure 12 depicted a further settling or subsidence and thickening of the turbidity layer by the August survey. This figure also displayed what appeared to be two sources of turbidity from the lake floor. One source is in the upper reaches of the lake on the Cumberland River. This inflowing turbidity appears to be a portion of the influx of the May storm event which had already begun to settle and disperse as a layer. Of particular interest was the turbidity which appeared to originate from a drop-off in the lake floor near Burnside, Kentucky. This input of suspended material may have been caused by several factors. The drop-off is in the vicinity of a number of substantial tributaries. An increased flow of water from upstream of the drop-off could scour and resuspend particles which might previously

have settled out on the plateau. An underflow moving down the lake could scour the ledge as it plunges to its interflow depth at the drop-off. Based on the temperature isotherms shown in Figure 15 for August, this does not appear likely. Releases from Laurel Dam could, however, produce such a cold water underflow during the summer months. Other possibilities are waves or currents produced in the main body of the lake which might strike the drop-off and produce turbidity by erosion. In any case, the answer probably lies with an understanding of the flow patterns and velocities of that particular area.

105. The temperature charts for June, July, and August have been included as Figures 13, 14, and 15. These are included in order to compare the subsidence of the turbidity layer with that of the thermally stratified water layers. By examining the turbidity results displayed by Figures 10, 11, and 12, the total or gross settling velocity of the turbidity layer could be closely approximated. This was accomplished by estimating the elevation of the center line of the turbidity layer in each of the three months. The procedure was repeated for the temperature isotherms of Figures 13, 14, and 15 at about the same depth. As the cooler, deeper waters were released from the dam through the generator intakes located at 610 to 630 feet, the thermal layers subsided over the two-month period. These monthly elevation drops were subtracted from the elevation losses of the turbidity layer for the same period. This resulted in a measure of how far the turbidity layer would have dropped exclusive of temperature layer subsidence and if no withdrawal had taken place. Based on the assumption that this net drop in elevation by the turbidity layer represented the average settling velocity of particles present in the layer, the average particle-

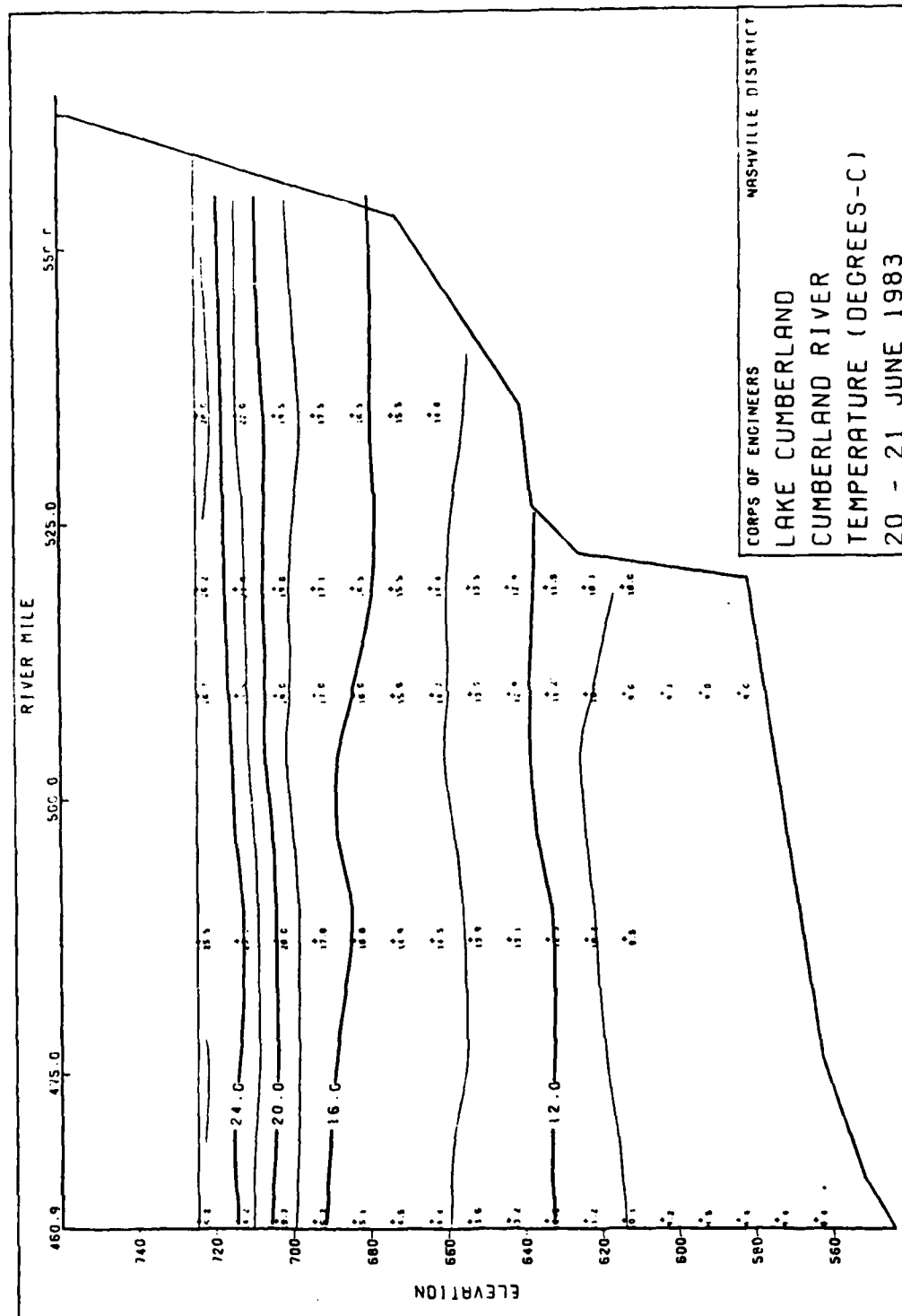


Figure 13. Temperature Results of the June Survey

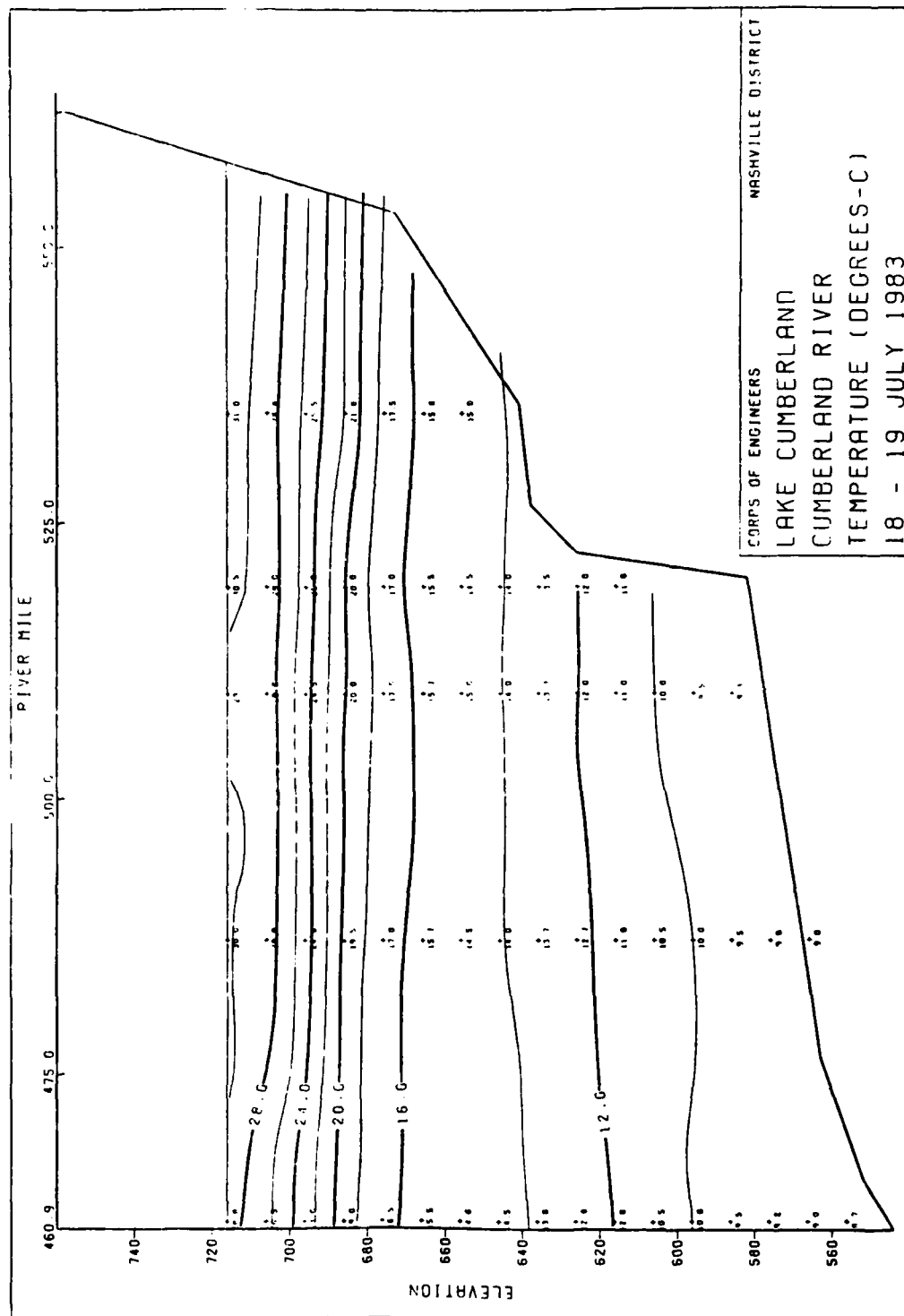


Figure 14. Temperature Results of the July Survey

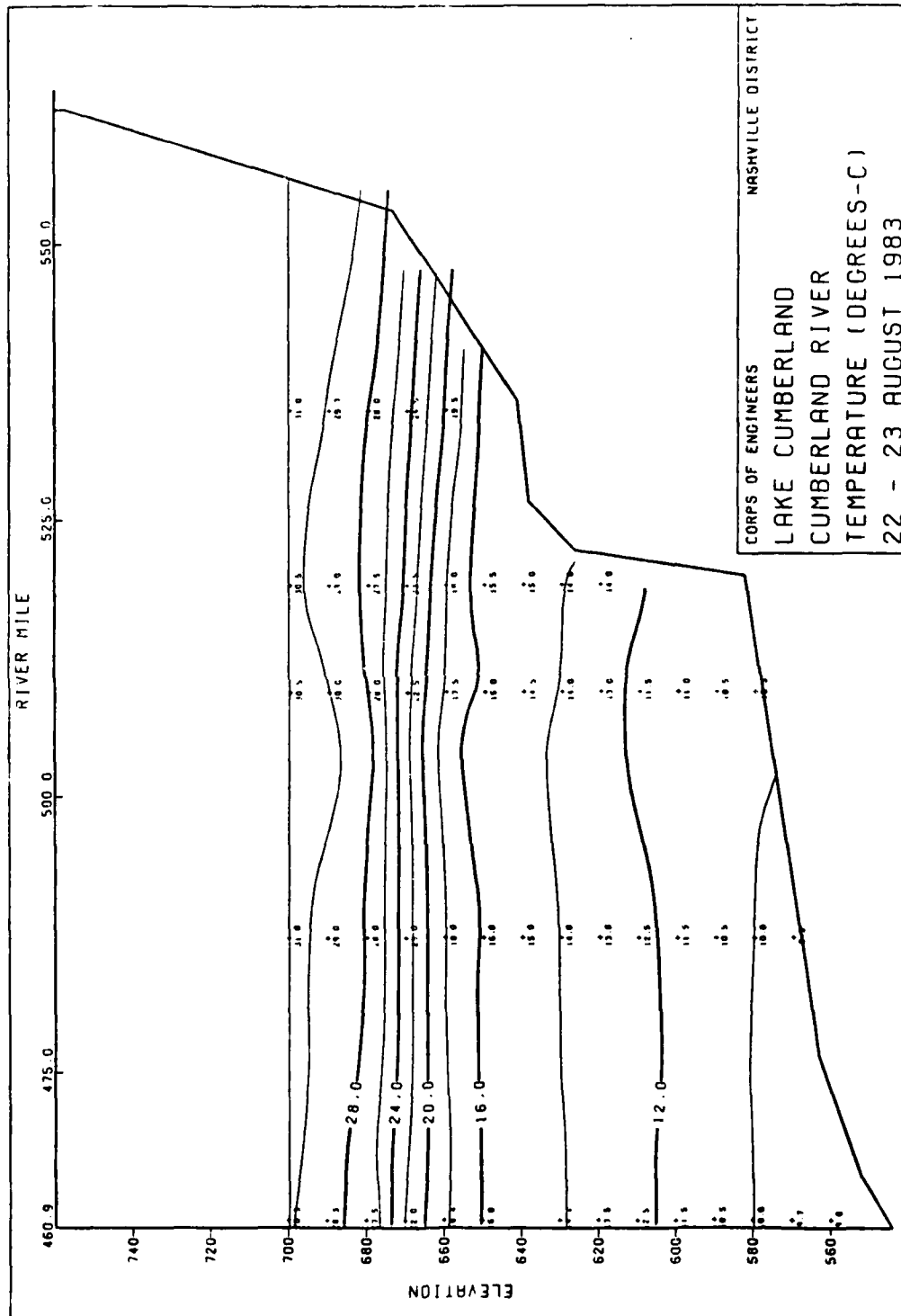


Figure 15. Temperature Results of the August Survey

settling velocity was estimated. This was accomplished by dividing the net subsidence of the turbidity layer by the time elapsed between the surveys.

106. Tables 2 and 3 present the data used in this procedure along with several computations of net turbidity layer subsidence velocity. The water subsidence values were obtained by using two isotherms, 14° and 16°C. Table 3 also displays values obtained for the gross subsidence velocity of the turbid layer. Table 4 was constructed to show the approximate periods of time required for the average layer-settling velocities to cause settling over a range of depths in the absence of and in the presence of thermal-layer subsidence.

107. These results indicated that in the absence of thermal-layer subsidence, the turbidity layer would require about 208 days or 7 months to settle 140 feet. For that same depth in the presence of thermal-layer subsidence, about 120 days or 4 months would be required. It should be remembered that these time periods are for the center line of the turbidity layer to settle this depth. The upper half of the layer would still be in the settling process. The elevation of the outlet, initial elevation of the turbidity interflow, and transit time through the lake are all important factors in determining if these long periods will allow the turbidity layer to be passed through the dam. In addition to these factors, the natural processes of stratification, overturn, and the timing of the storm event causing the inflow of turbidity can determine if the turbidity is passed downstream. If the inflow occurs before stratification, an interflow layer would probably not form. This would result in a much longer transit time through the lake but would also reduce the particle-settling velocities

Table 2. Data of Thermal- and Turbid-Layer Subsidence Tracking

Month	Δ Drop	Height Turbidity Center Line (feet)	Δ Drop (feet)	Elevation of 14°C (ft) Isotherm	Δ Drop (feet)	Elevation of 16°C (ft) Isotherm	Δ Drop (feet)	Temperature at Center Line of Turbidity
June		687		658		686		16.1
	28		35		13		16	
July		652		645		670		14.5
	35		38		15		18	
August		614		630		652		12.7

Table 3. Subsidence Velocity Computations

	Including Thermal Subsidence	Excluding Thermal Subsidence	
		14° Isotherm	16° Isotherm
June to July	35'/28 days = 1.25 ft/day	35' - 13' = 22' 22'/28 days = 0.785 ft/day	35' - 16' = 19' 19'/28 days = 0.678 ft/day
July to August	38'/35 days = 1.085 ft/day	38' - 15' = 23' 23'/35 days = 0.657 ft/day	38' - 18' = 20' 20'/35 days = 0.571 ft/day
Average	1.167 ft/day	0.673 ft/day	

Table 4. Times Required for Turbid-Layer Settling
With and Without Thermal-Layer Subsidence

Depth Layer Center Line Must Drop to Impact Bottom (Feet)	Time Required Assuming Average Particle- Settling Velocity of 0.67 ft/day (Days)	Time Required Assuming Average Particle- Settling Velocity of 1.16 ft/day (Days)
200	297.1	171.3
190	282.2	162.7
180	267.4	154.1
170	252.5	145.6
160	237.7	137.0
150	222.8	128.4
140	208.0	119.9
130	193.1	111.3
120	178.3	102.8
110	163.4	94.2
100	148.5	85.6
90	133.7	77.1
80	118.8	68.5
70	104.0	59.9
60	89.1	51.4
50	74.3	42.8
40	59.4	34.3
30	44.6	25.7
20	29.7	17.1
10	14.8	8.6

since there would be no thermal layer subsidence. In the case of a storm occurring after stratification, the inflow would act as a turbidity or density flow and initially insert itself further down the length of the lake. However, the apparent settling velocity would be greater with the aid of the thermal-layer subsidence. In the event of fall overturn, the particles of the turbidity layer would become resuspended and thus not be allowed to contact the lake bottom. While this would result in a longer period being required for the particles to settle out, the turbidity layer would no longer exist as a layer but would be diluted throughout the depth of the lake preventing any substantial turbidity increases in the water released downstream. This would also explain why the turbidity throughout the lower half of the lake is greater in March than while the layer is present in August.

Suspended Solids

108. The charted results for the suspended solids tests taken in the April through August survey trips are shown as Figures 16 through 20. The primary purpose of these Figures was to collaborate and reinforce the previously discussed information gained by the use of the turbidity charts.

109. The seasonal influences on suspended solids inflow were again demonstrated beginning with Figure 16 for April which shows an increasing concentration of suspended solids travelling unstratified down the upper third or plateau portion of the lake. With the influx of the May storm runoff, suspended solids concentrations of 10 mg/l or greater had moved about two-thirds of the distance down the lake.

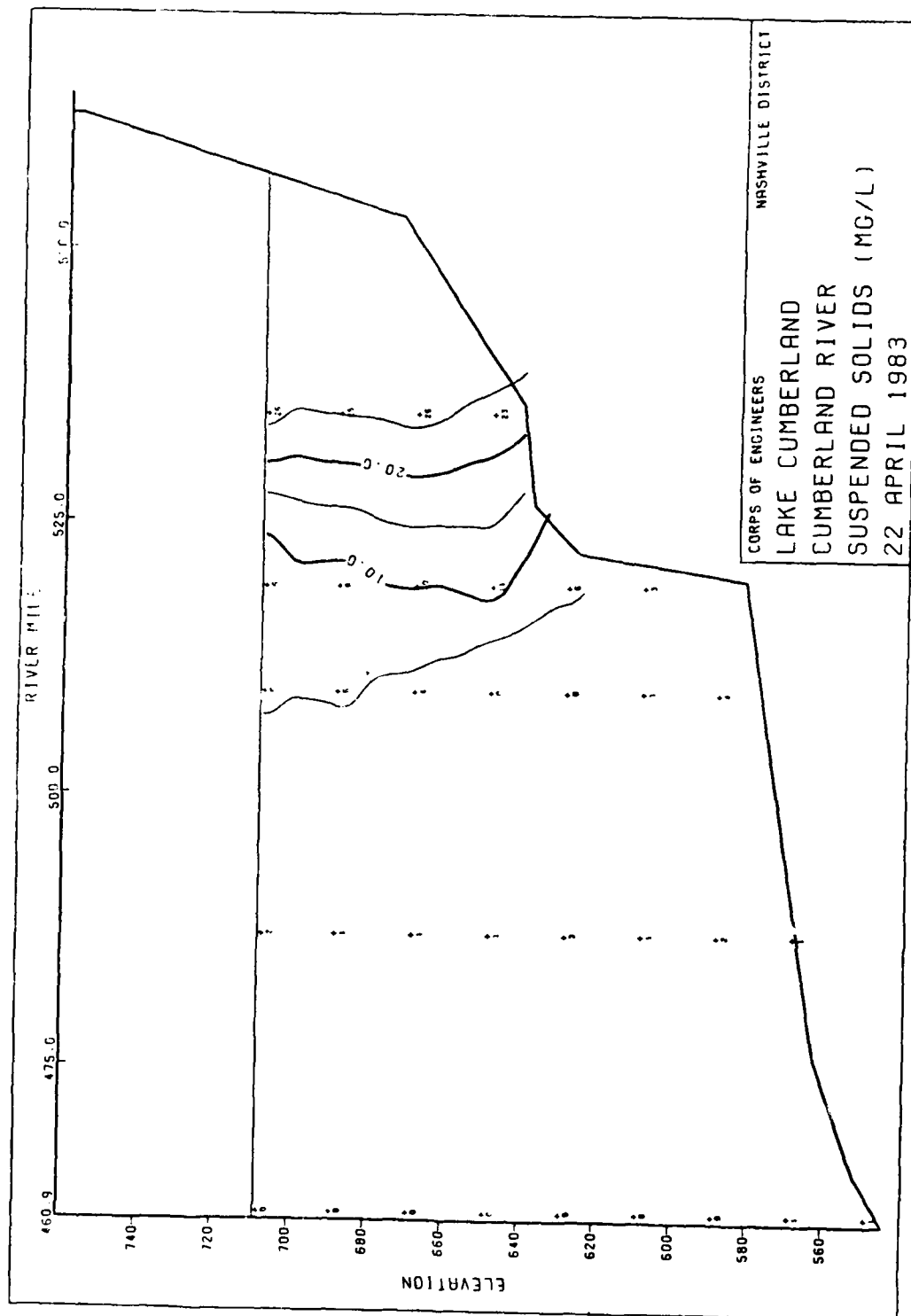


Figure 16. Suspended Solids Results of the April Survey

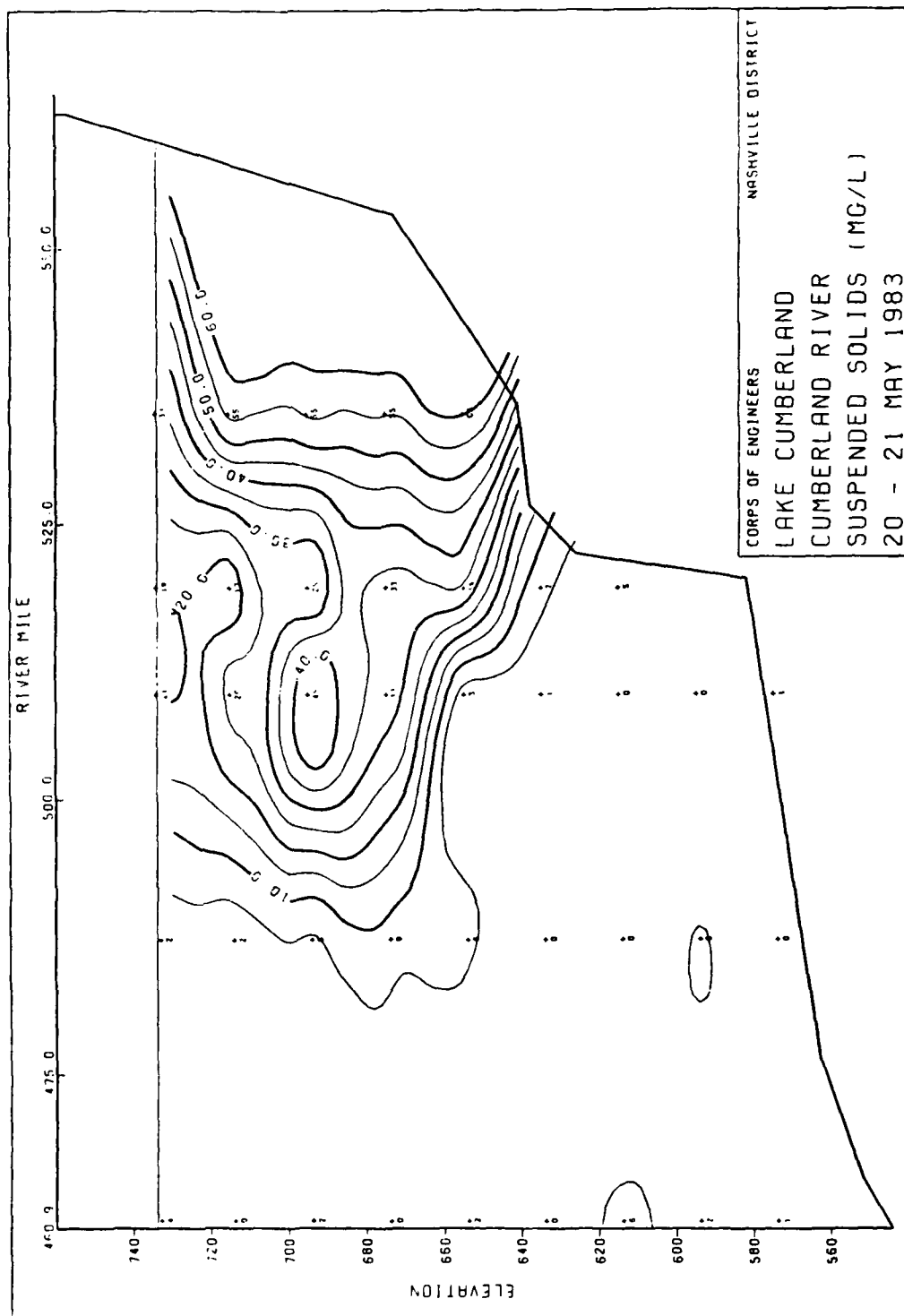


Figure 17. Suspended Solids Results of the May Survey

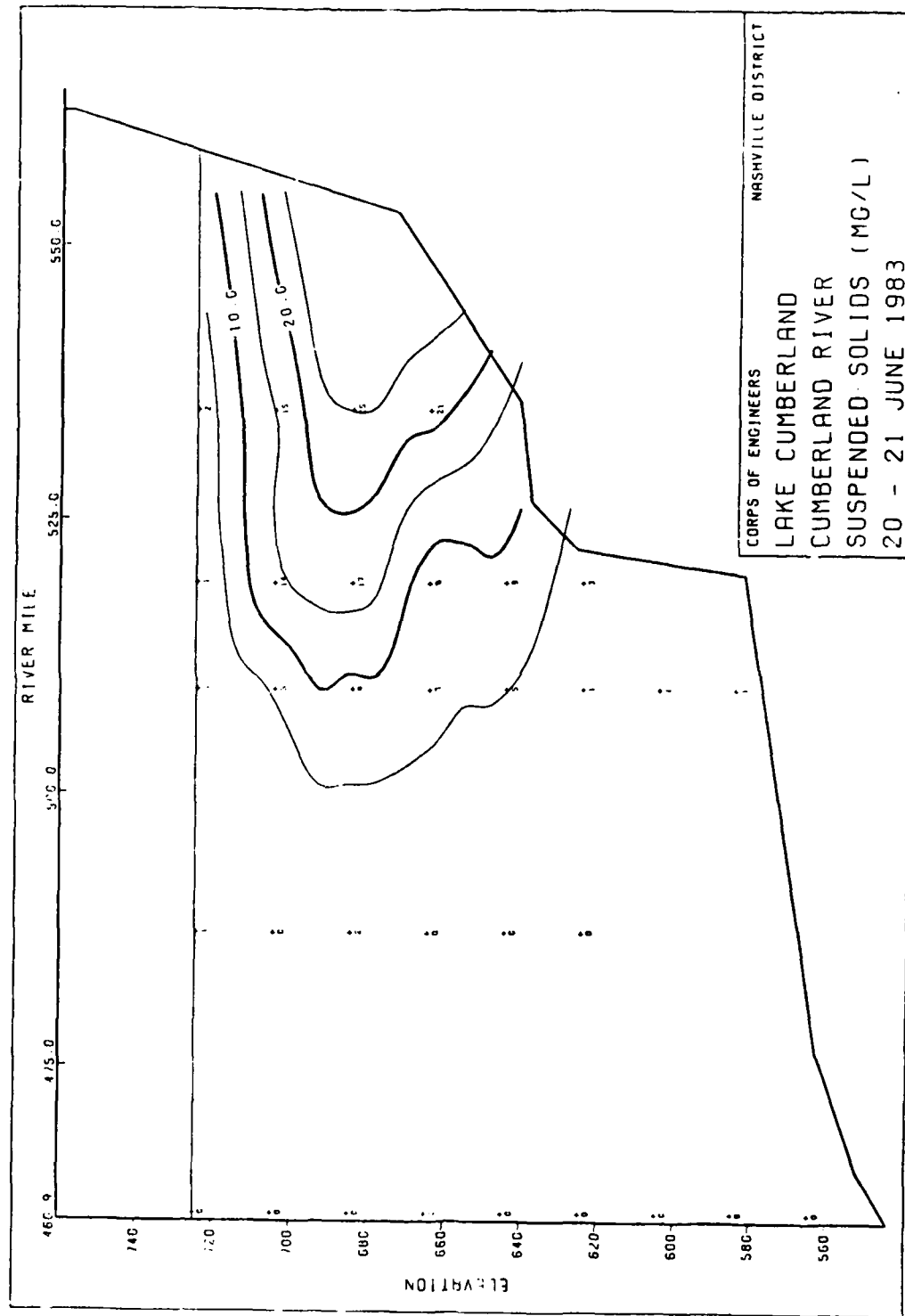


Figure 18. Suspended Solids Results of the June Survey

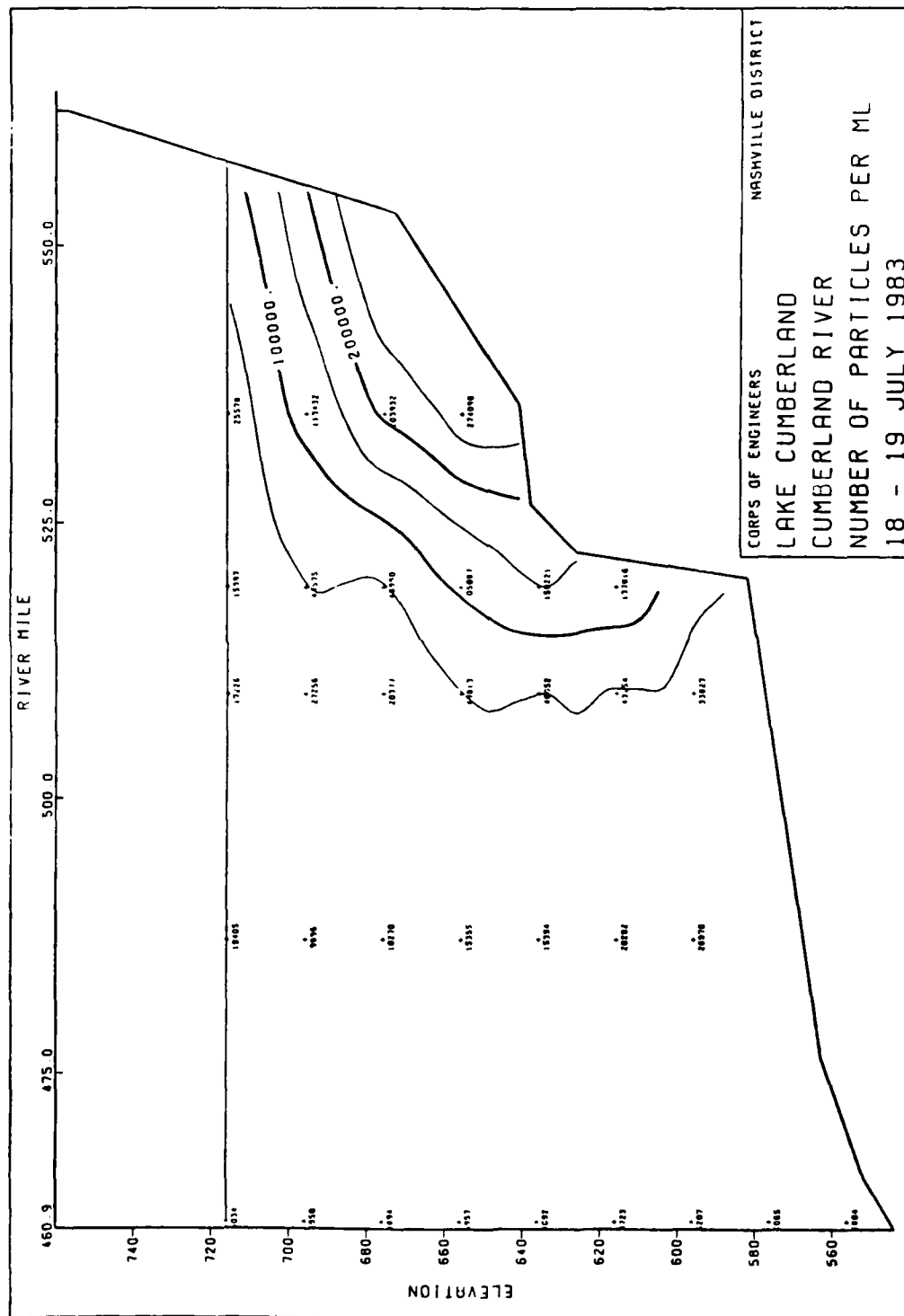


Figure 19. Suspended Solids Results of the July Survey

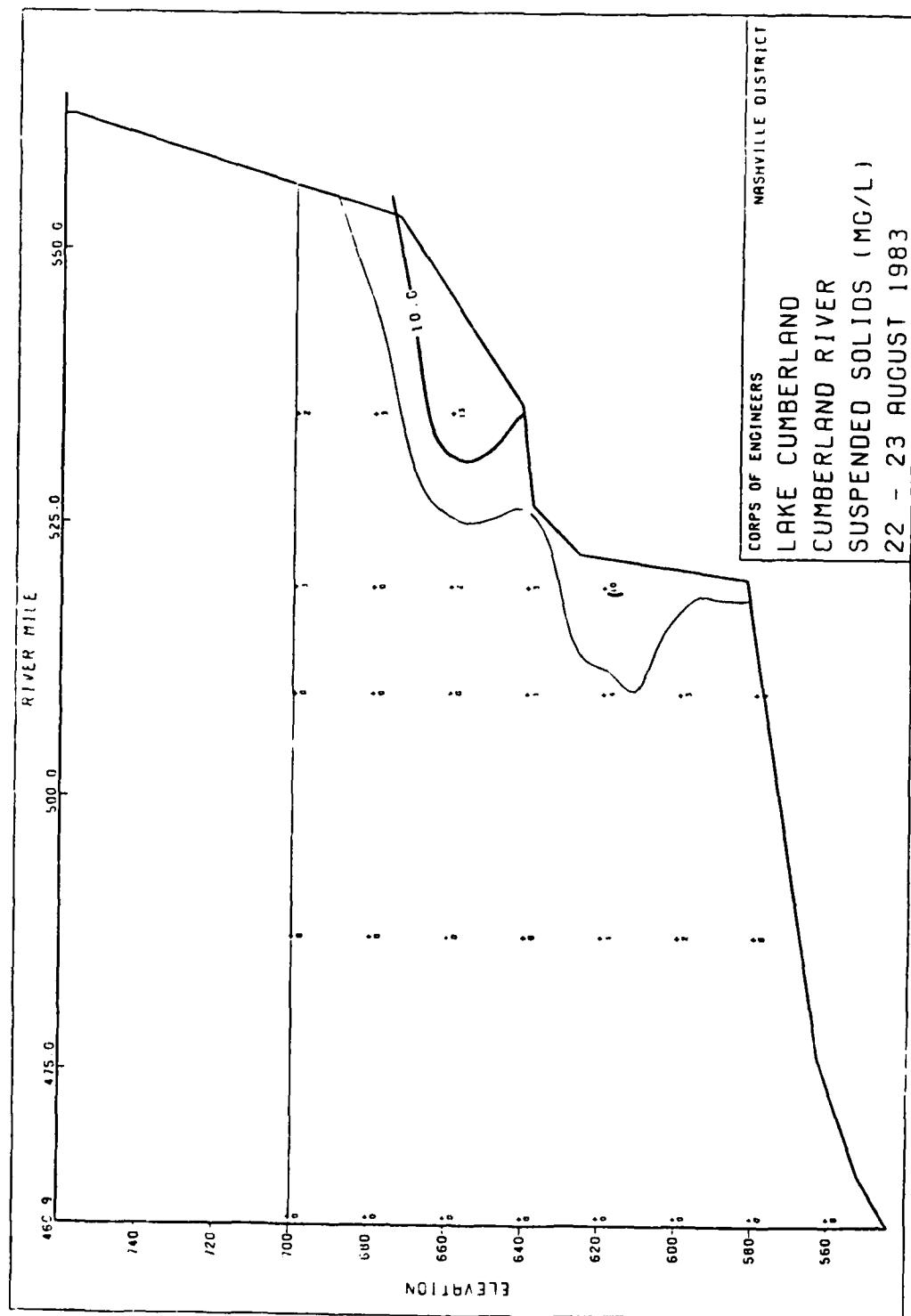


Figure 20. Suspended Solids Results of the August Survey

Through June and July the concentrations dropped and retreated up the lake until the concentrations became less than those present in April. This indicated that the particles retained by the filter used in the suspended solids test were of a size which quickly settled out under normal conditions.

110. The August figure completed this cycle of seasonal input of suspended solids by indicating that the two apparent sources of turbidity discussed previously may only be the settling of the layer, a portion of which settled on the plateau leaving the forward tip of the layer to appear extended from the drop-off. While this explained the removal of suspended solids in this area, a comparison of turbidity and suspended solids charts for August showed that the smaller particle sizes which were constituents of turbidity were being influenced by other forces.

111. A comparison of the turbidity and suspended solids results for the five surveys indicated a close relationship between high turbidity measurements and suspended solids concentrations. This confirmed that turbidity was caused by suspended particles. Additionally, the relationship indicated that particles which were for the most part smaller than those retained in suspended solids tests were the primary constituents of water having turbidity measurements of less than 20 NTU.

112. The June survey results demonstrated that thermal stratification had a much smaller effect on suspended solids than on turbidity. This was again due to the larger size of the particles which were retained in the suspended solids test. By settling faster, these

larger particles resulted in a layer which did not extend as far down the lake and which was much thicker despite stratification.

Particle Examination Tests

113. Excluding the turbidity tests, the majority of information discovered about the dynamics of the lake system were derived from the results of particle examination tests. The particle-number counts, particle-size distribution, zeta potential, and other tests performed on the suspended sediment itself all provided valuable information. For this reason, each of these tests and their results will be discussed in detail over the following pages.

Particle Number Count

114. A discussion of particle-number-count results would not be possible without additional explanation of how these results were obtained. The HIAC instrument used was able to count the total number of particles in a sample of any given size. Throughout the survey trips, the sample size tested by this instrument was maintained at ten milliliters. As the sample passed through the sensor, the particles were counted and the final number displayed. This was followed by the automatic plotting of the particle-size distribution. The number of particles shown on the counter was then noted on that sample plot by the operator. Any additional information such as dilution factor or change in sample size was also recorded along with the sample number and date. Upon returning from each survey, this number was converted to the number of particles per milliliter and forwarded to the Nashville District office to be plotted by computer. These completed charts for the number

of particles per milliliter are included for the May through August surveys as Figures 21 through 24.

115. By comparing the charts of particle count per milliliter with those of turbidity and suspended solids for each successive survey trip, a strong relationship between the three measurements was observed. Initially a linear relationship between suspended solids and number of particles seems logical except for the possibility of the number count being based solely on very fine particles. However, based on the information cited in a review of the available literature, a lognormal size distribution would be expected for the suspended particles. The references also indicated that the size distribution of particles present in an individual system, as well as the particle composition, tended to remain constant. This means that any flow from that source should contain a relatively constant percent of its suspended sediment load in each size range. This results in the concentration of the larger particles, measured by suspended solids, varying in direct proportion to the total sediment load.

116. The strong relationship between turbidity and number of particles can be seen throughout the monthly survey charts. Since particle size and number are the two principal influences on turbidity readings, this relationship seemed reasonable. A comparison of turbidity and particle counts for June and July display the strong association between very high particle counts and high turbidity readings. In both months, however, the turbidity effects were noticeable further downstream than were the elevated particle counts. This was probably due to the flocculation of many small particles into single large particles as the turbid flow moves down the lake. These

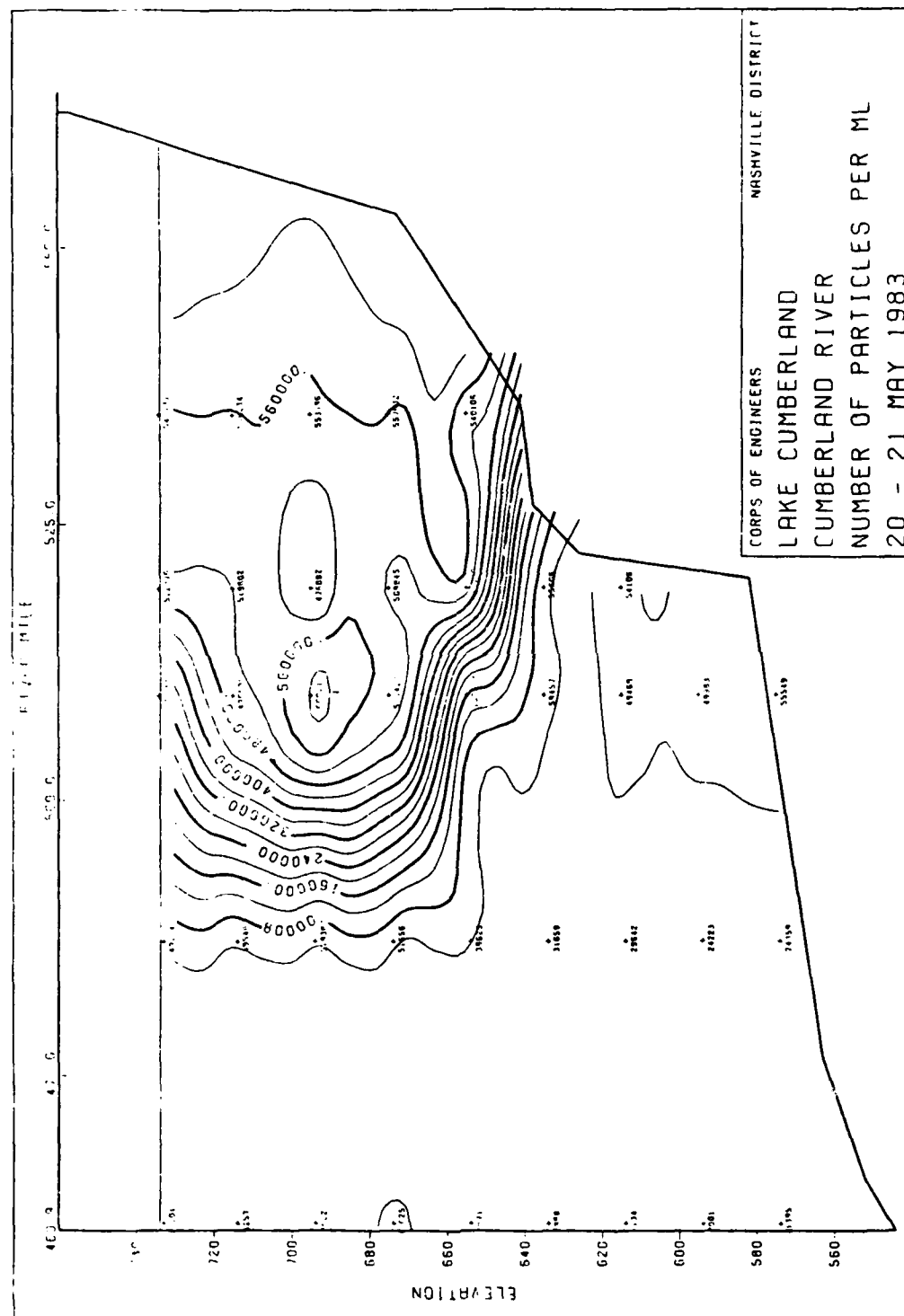


Figure 21. Particle Count Results of the May Survey

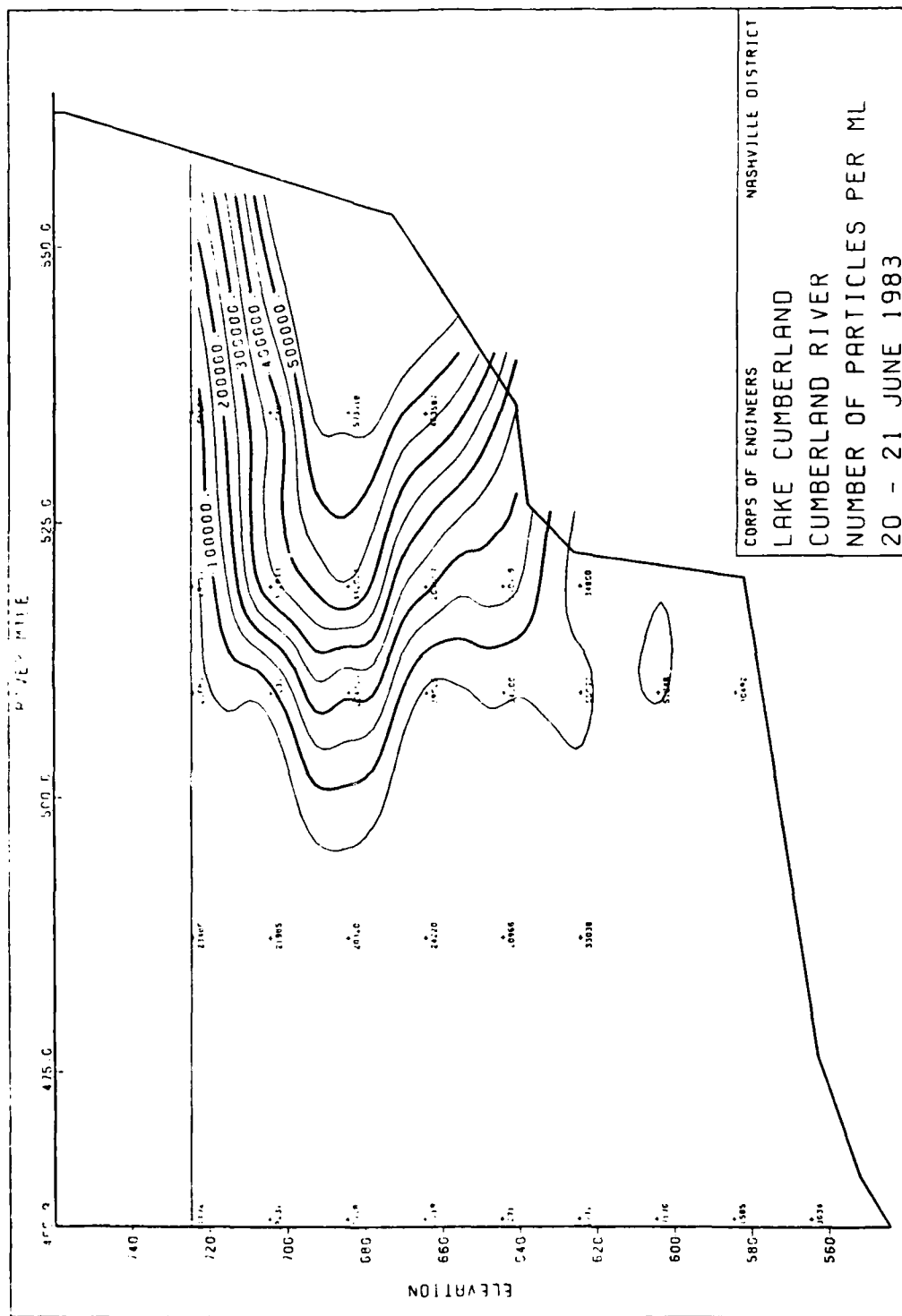


Figure 22. Particle Count Results of the June Survey

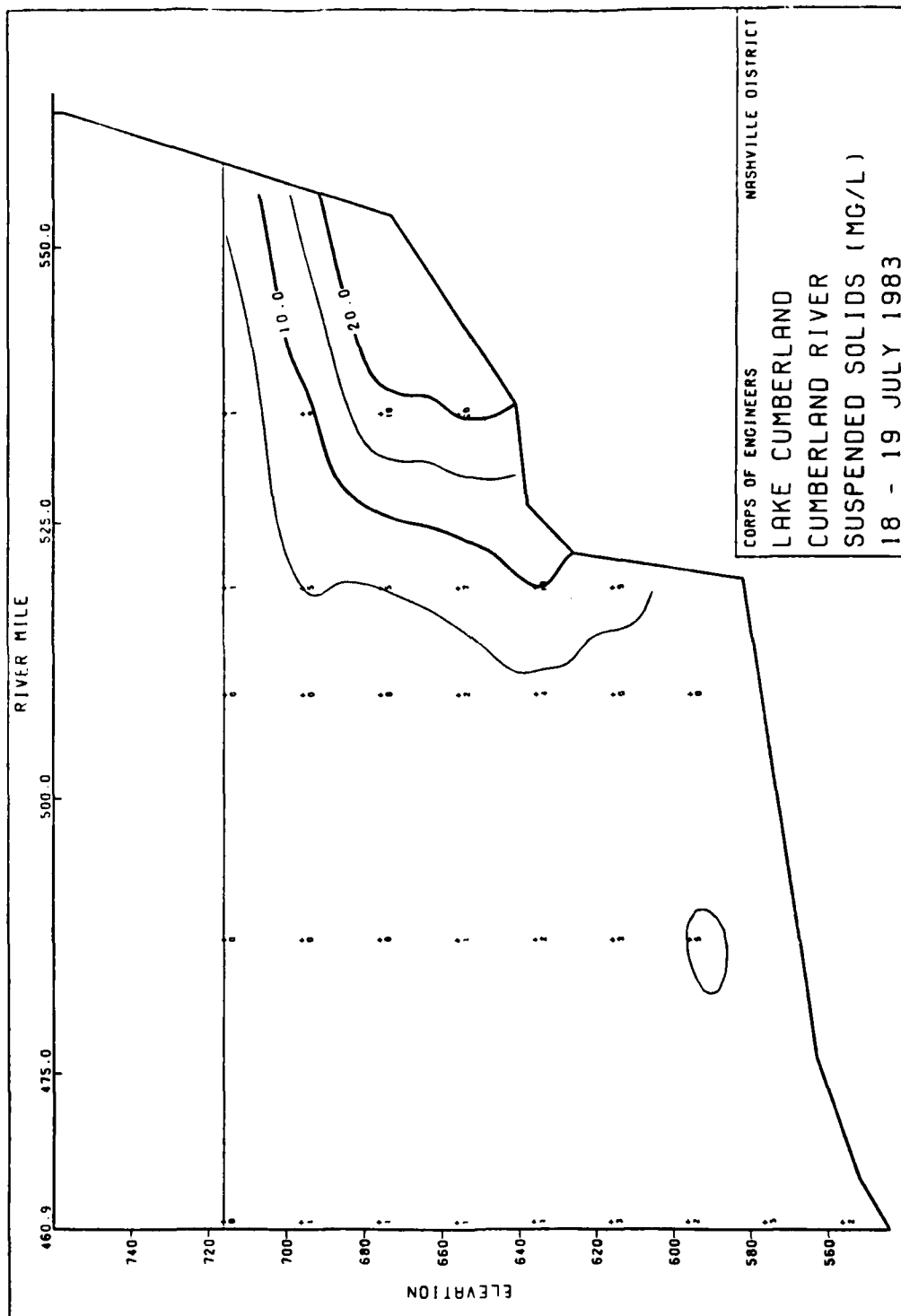


Figure 23. Particle Count Results of the July Survey

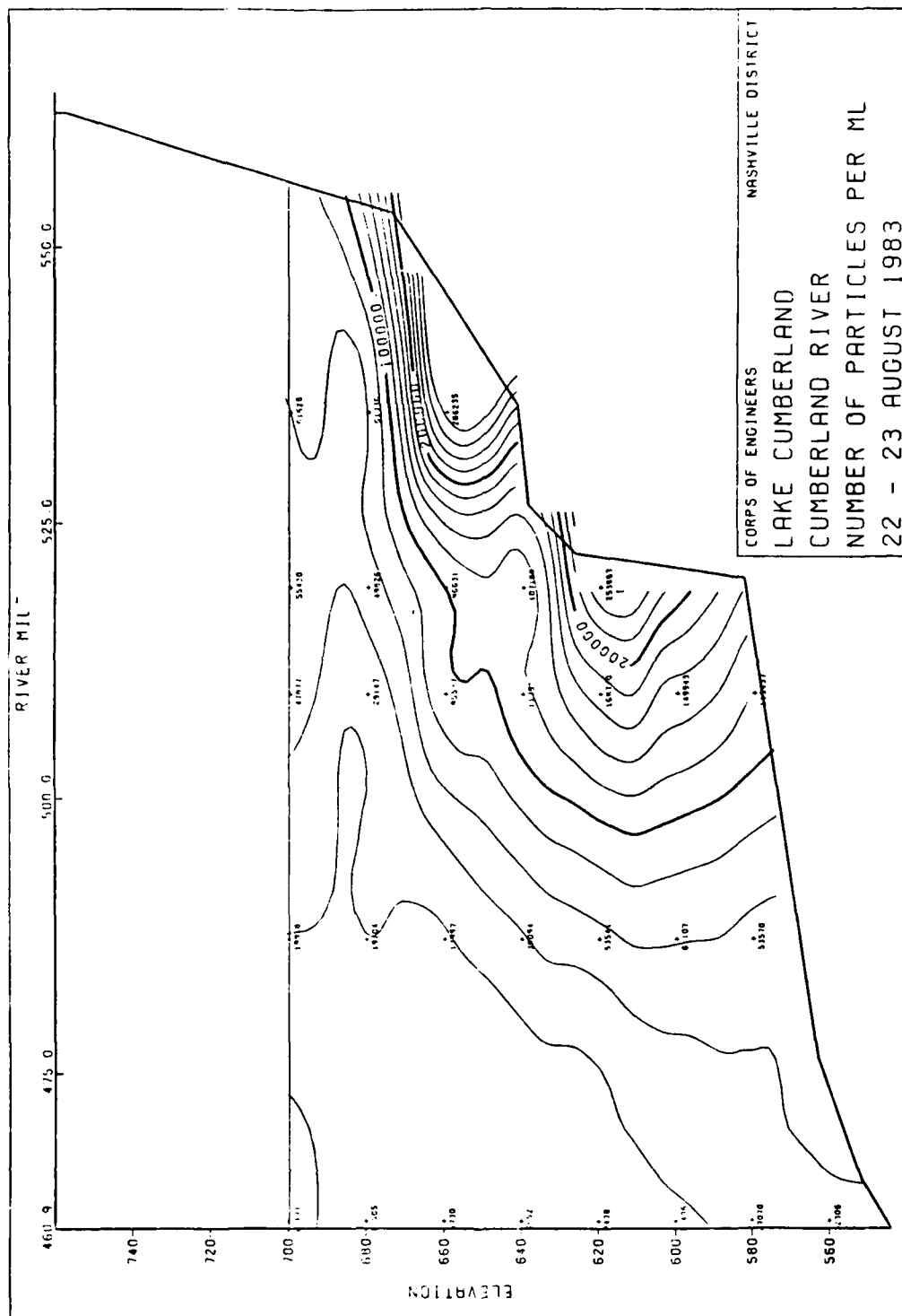


Figure 24. Particle Count Results of the August Survey

flocculated particles remained capable of producing relatively high turbidity readings.

Particle-Size Distribution

117. Particle-size distribution has already been mentioned many times in the discussions of the previous test methods and their results. The size of the particles can greatly influence both turbidity and suspended solids. In a system where suspended particle composition remains constant, particle size becomes the prime determinant of settling or suspension.

118. A plot of the size distribution for each sample was made by the HIAC instrument. Each distribution was plotted as a percent of the number of particles present in a sample less than a specific size. By choosing a specific size, the percent of particles less than that size could be determined for each sample. The sizes of 2, 4, 8, 16, 31, 62, 125, and 250 μm were chosen and the percent less than these sizes was determined for each sample from the HIAC plots. This information was forwarded, with the other results of each survey, to the Nashville District to be computer plotted. The finished computer charts provided isograms of percentages less than these sizes for each survey. Unfortunately, these charts proved to be of little use in determining the particle sizes which remained suspended for long periods of time. An attempt was made to track the settling rate of particle concentrations in the various size ranges. This proved to be impossible because as the particles fell from suspension and the less-than isograms rose in elevation, the percent less-than values were also changing. Also, the rising isogram only indicated that larger particles were

falling without identifying any specific size ranges undergoing settling. For this reason, charts for the percent of particles less than certain sizes have not been included.

119. The size distribution data were useful, however, when combined with the particle count information. By multiplying the total number of particles by the percent of that sample within a size range, the number of particles of a particular size range could be calculated for each sample. This information was tabulated and plotted for the size ranges of less than 2, 2-4, 4-8, 8-16, and greater than 16 μm . These plots are included for the May and July surveys as Figures 25 through 34.

120. In a comparison of the two surveys for particles less than 0.002 mm provided in Figures 25 and 26, a substantial net loss of particles had occurred over the two-month period. The concentration of small particles near the bottom of the upper third of the lake did show an increase over time which suggests slow settling by these particles. A comparison of Figures 27 and 28 for the size range of 2-4 μm reveals that the increase of particle concentration in this same area was not as slow as for the smaller, less than 2 μm , particles. This trend continued for the 4-8 μm charts, Figures 29 and 30, which showed that this range of particles settled faster than the previous smaller size ranges but had not completely reached the lake bottom during the two-month period.

121. At this point, it should be explained that these trends are the apparent movement of particles over and above what might be considered as normal background concentrations. These normal background concentrations change each month for a number of reasons including the

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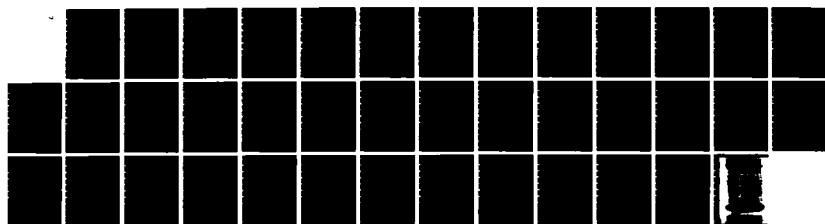
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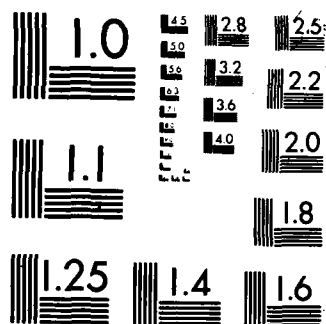
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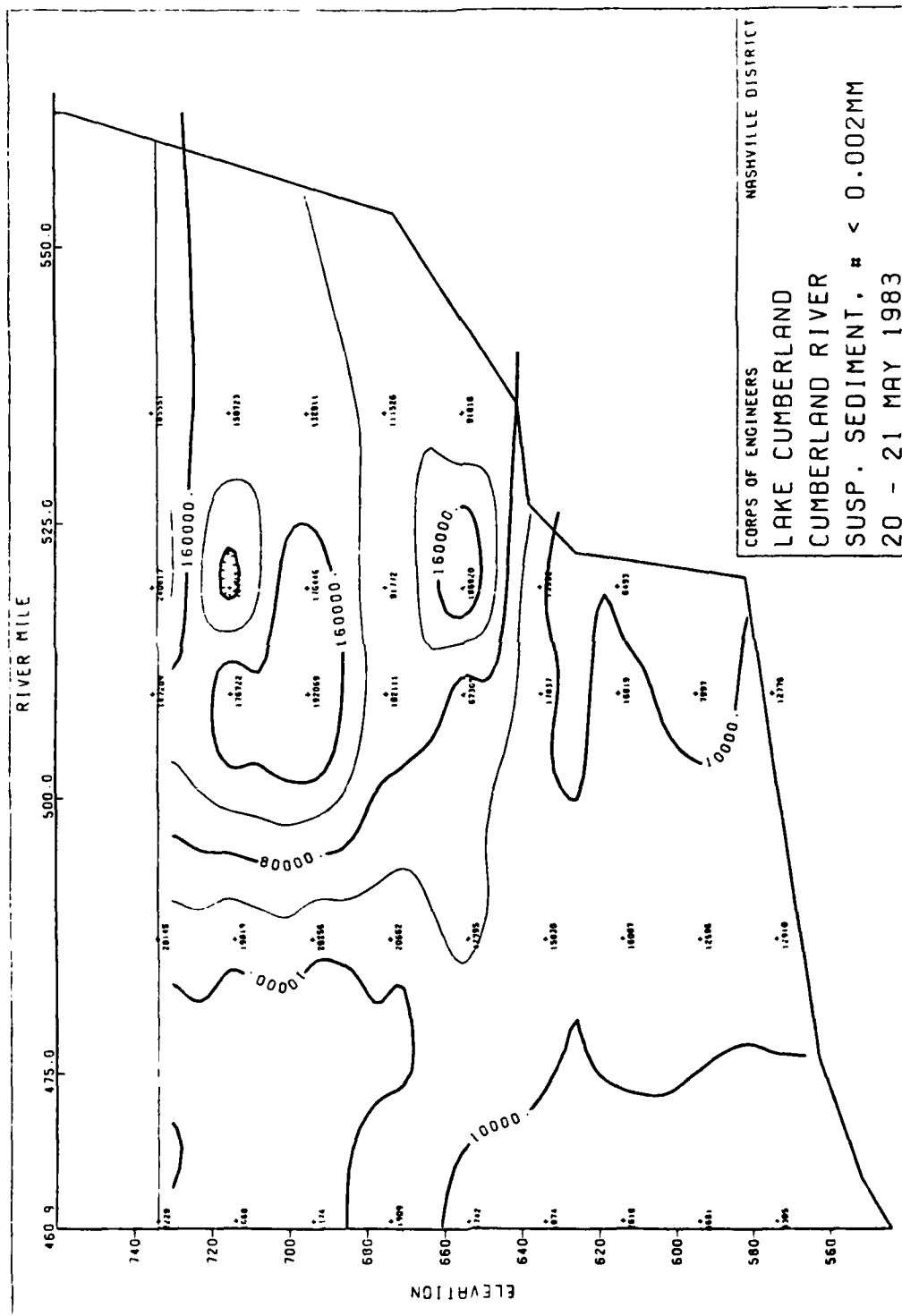
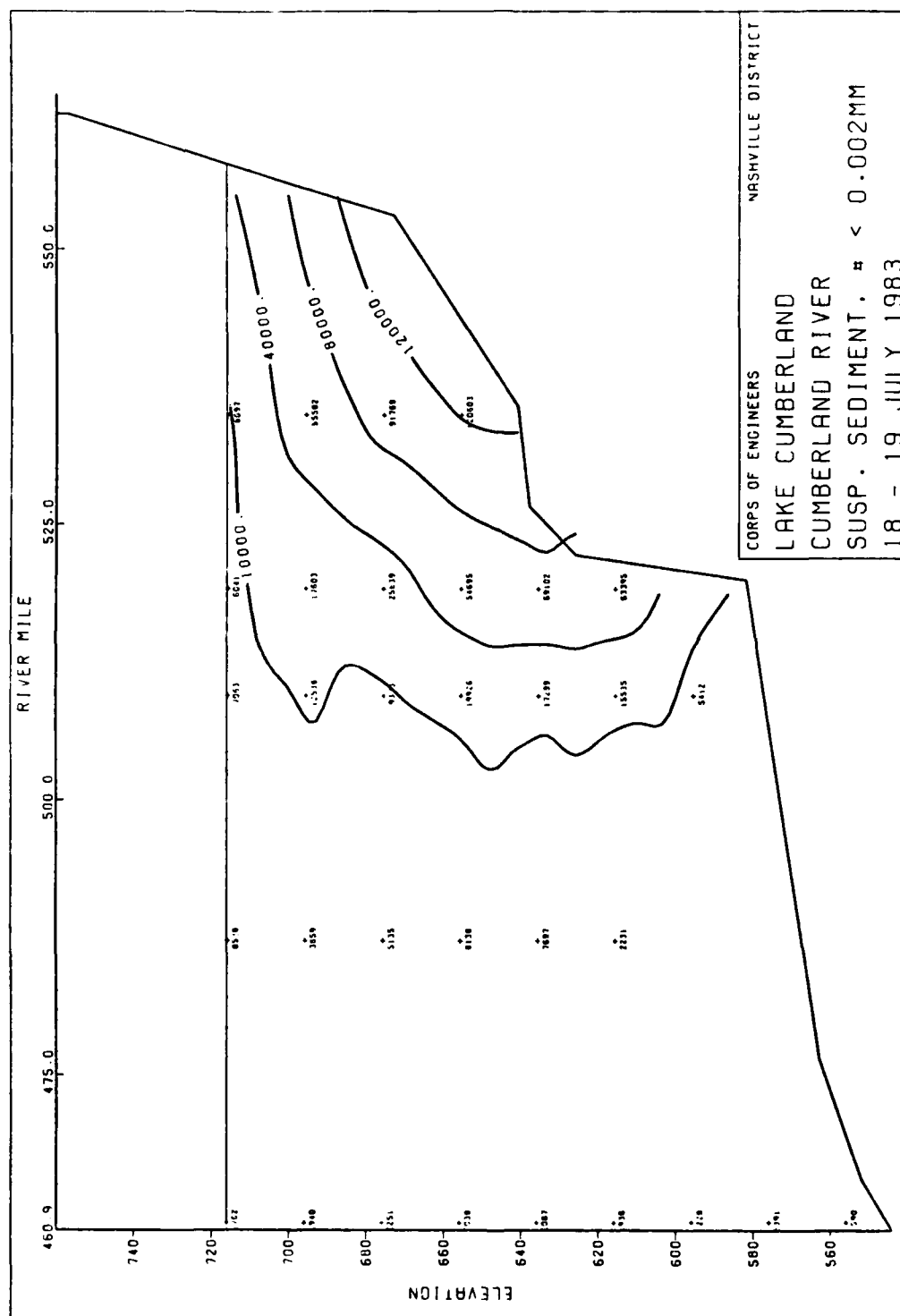


Figure 25. Number of Particles <2 μ m Present During May Survey



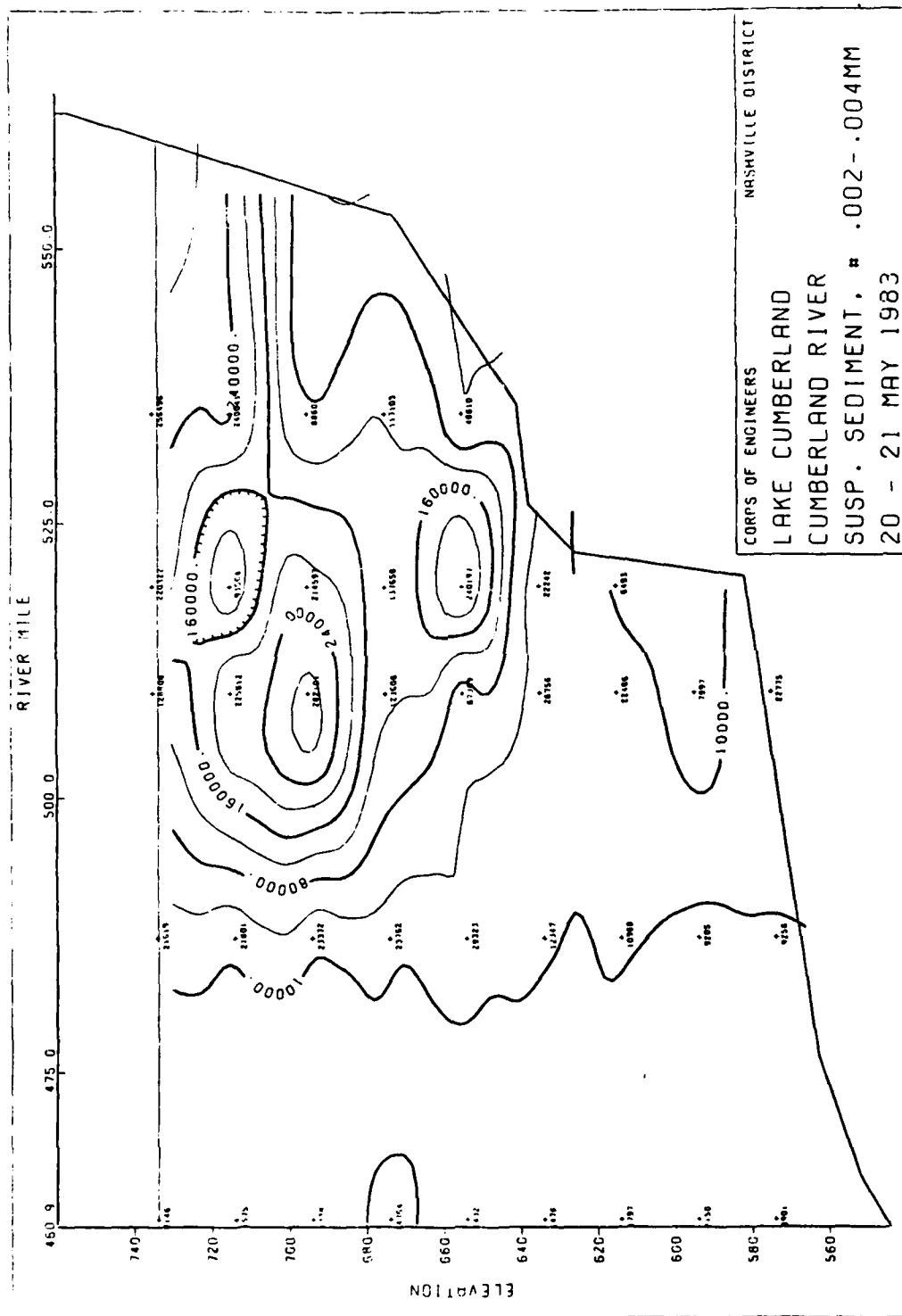


Figure 27. Number of Particles 2-4 μ m Present During May Survey

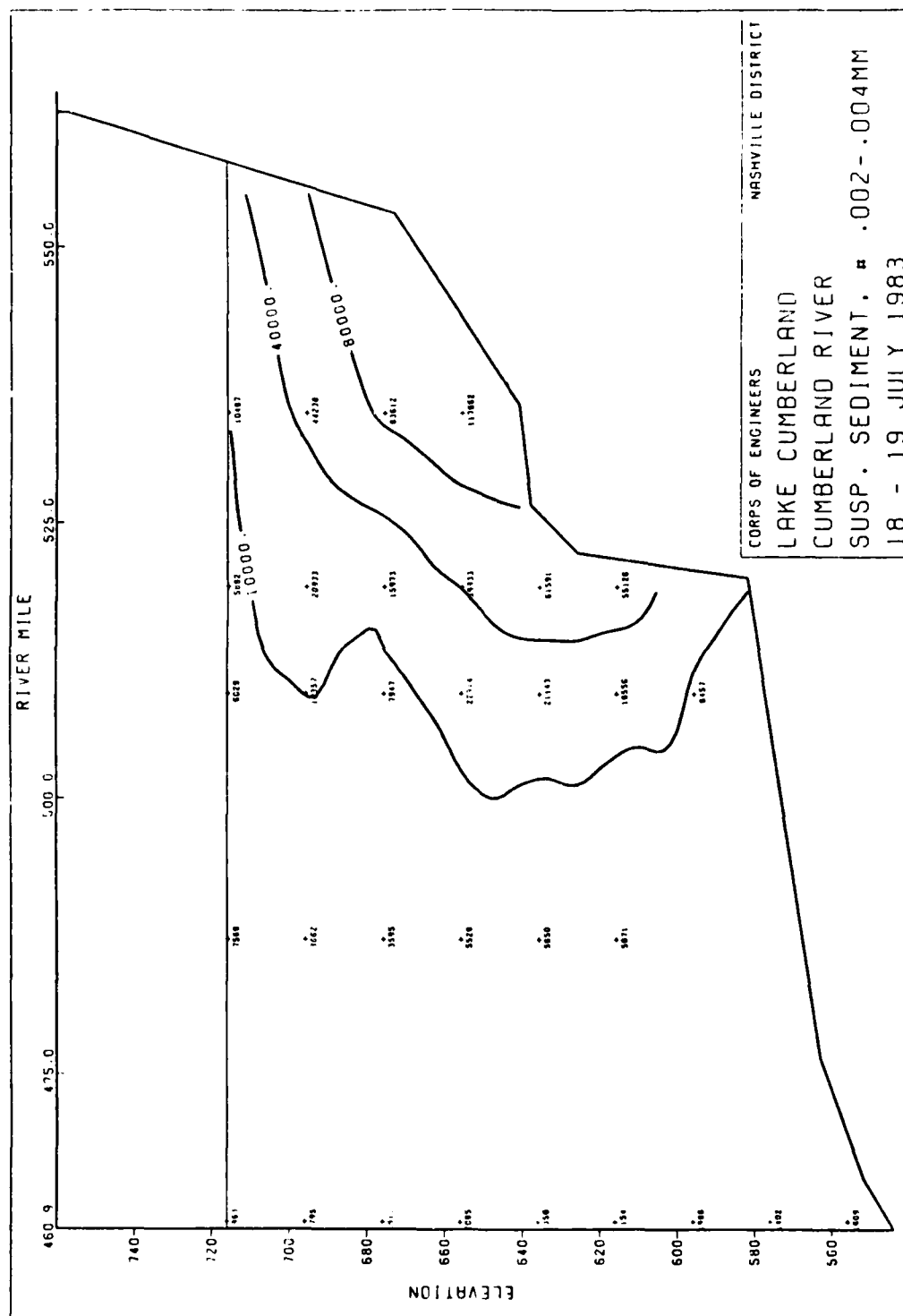


Figure 28. Number of Particles 2-4 μ m Present During July Survey

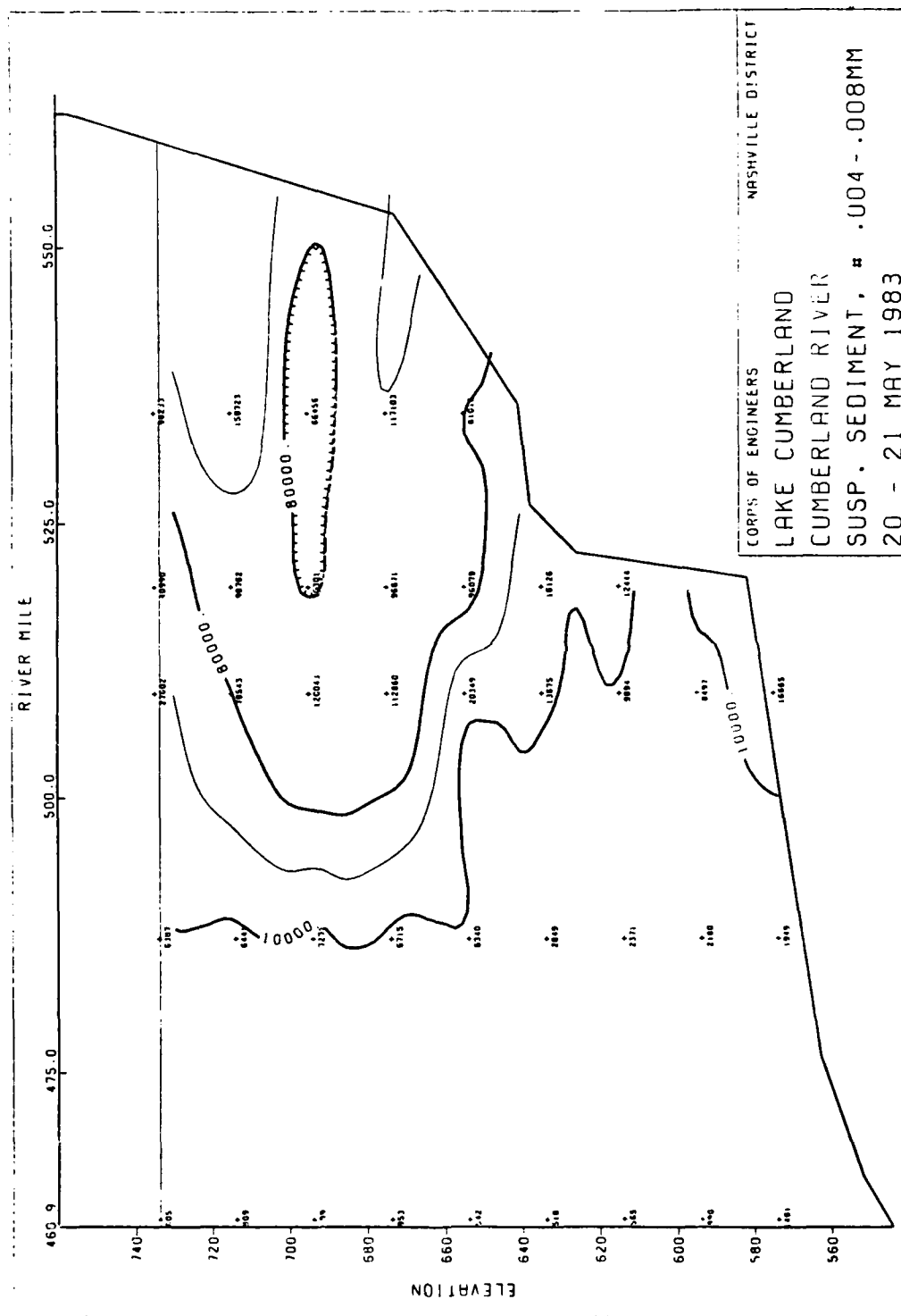


Figure 29. Number of Particles 4-8 μ m Present During May Survey

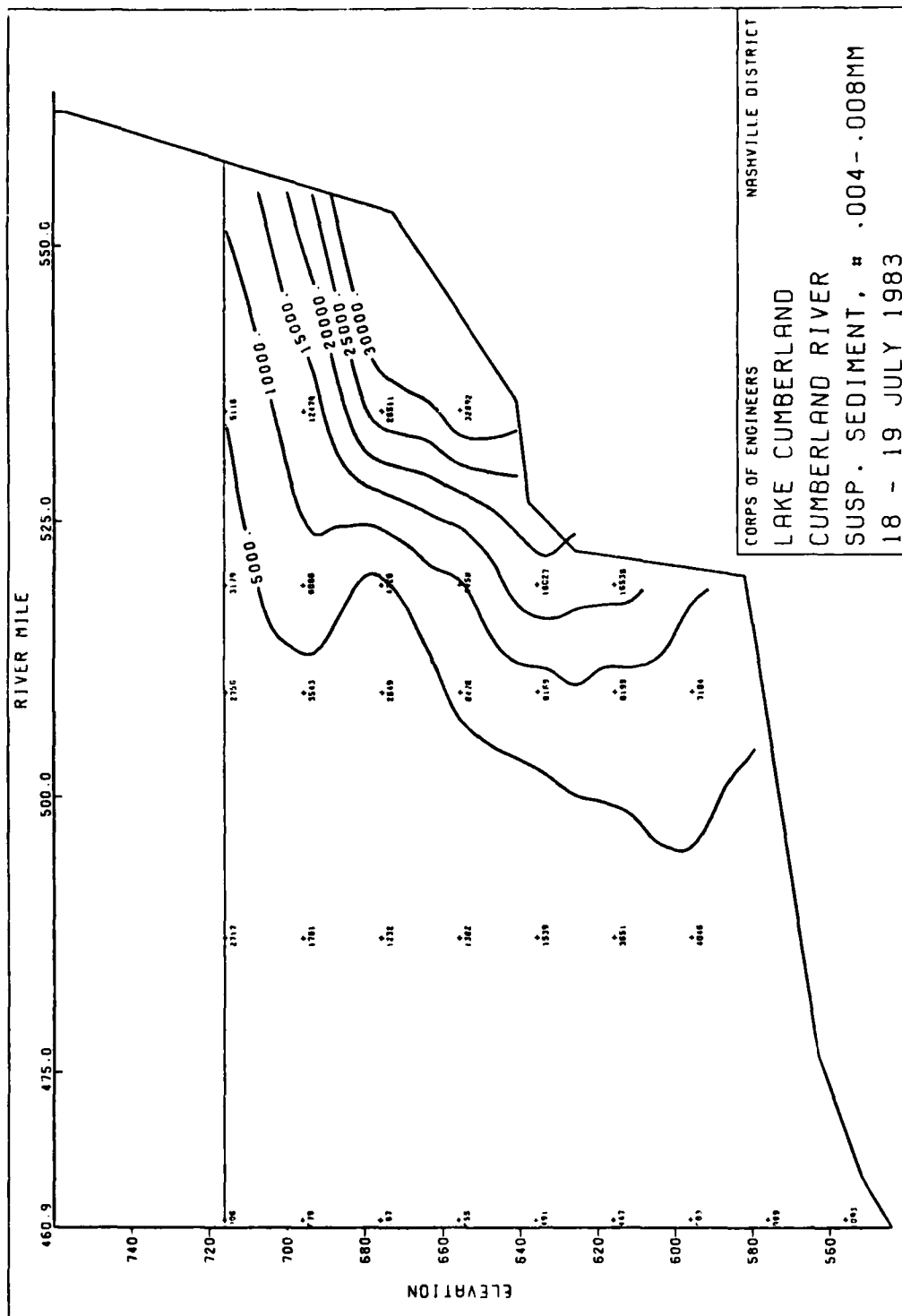


Figure 30. Number of Particles 4-8 μ m Present During July Survey

natural settling of particles, the flocculated settling of particles, the ingestion of particles by organisms, and the contribution of particles by organisms. Particle concentrations also change from influences outside the lake system such as additional particle input due to storm events or increased flows.

122. An examination of the 8-16 μm results displayed by Figure 31 and 32 demonstrated that practically all of the particles which might be considered higher than normal background concentration have settled out over the two-month period. This process was repeated in Figures 33 and 34 for particles greater than 16 μm . This indicated that the particles which remained in suspension for a period long enough to pass through the lake in 1983 had sizes of less than 8 μm . Since these comparisons were noted over only two months, and the transit time through the lake for an inflow was considerably greater than that, the actual size range for the particles reaching or passing through the dam may have been smaller. However, with the natural variables of stratification, overturn, and season and volume of inflow, the available settling period could be shortened and larger particles could pass through the lake.

Zeta Potential

123. The purpose of this examination was to determine the charge present on particles found within each sample to determine if the repulsive force of the charge was sufficient to produce a colloidal suspension. These data were also forwarded after each survey for computer plotting. These plots did show a slight relationship to concentrations of particles in specific size ranges. This indicated

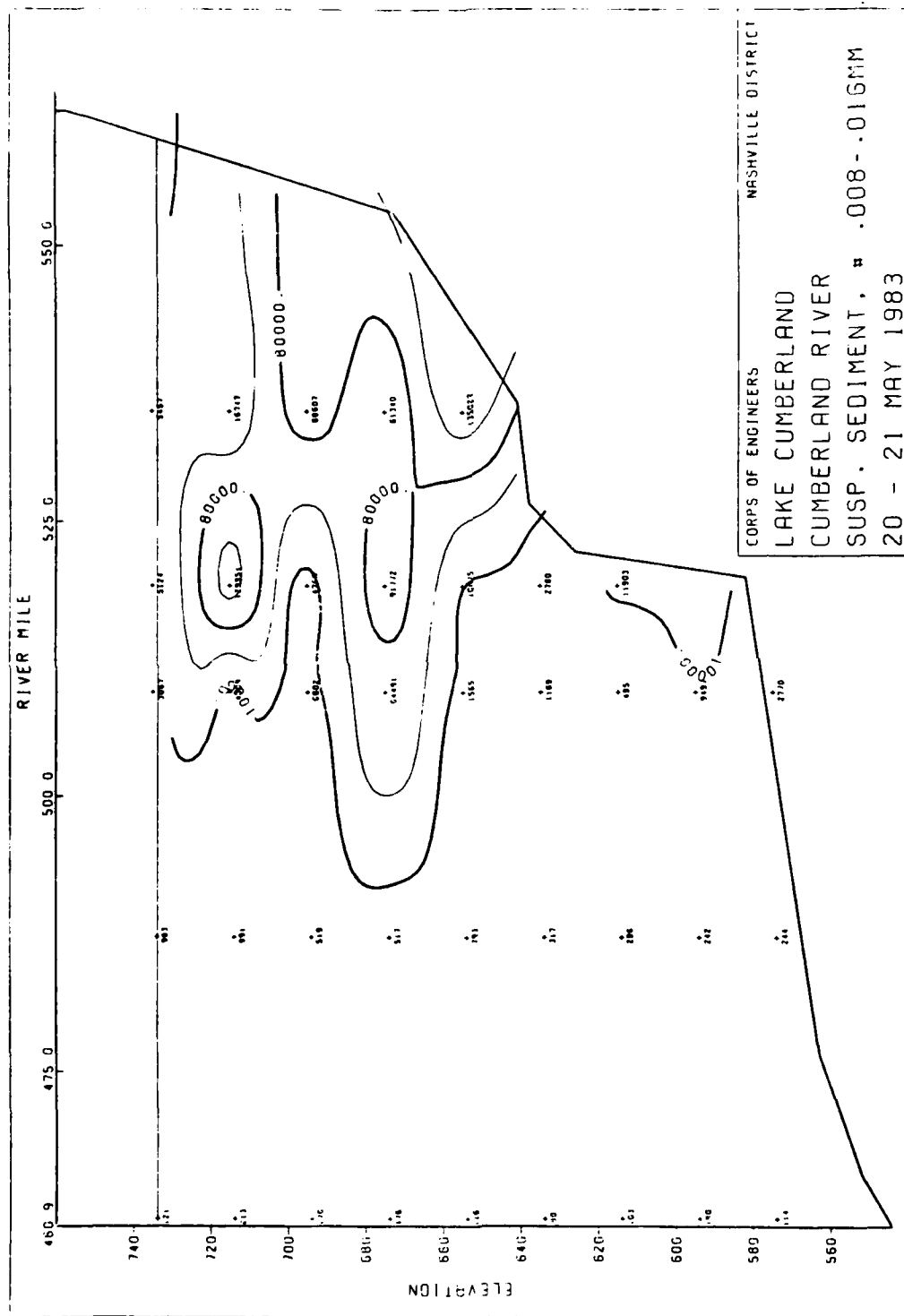


Figure 31. Number of Particles 8-16 μ m Present During May Survey

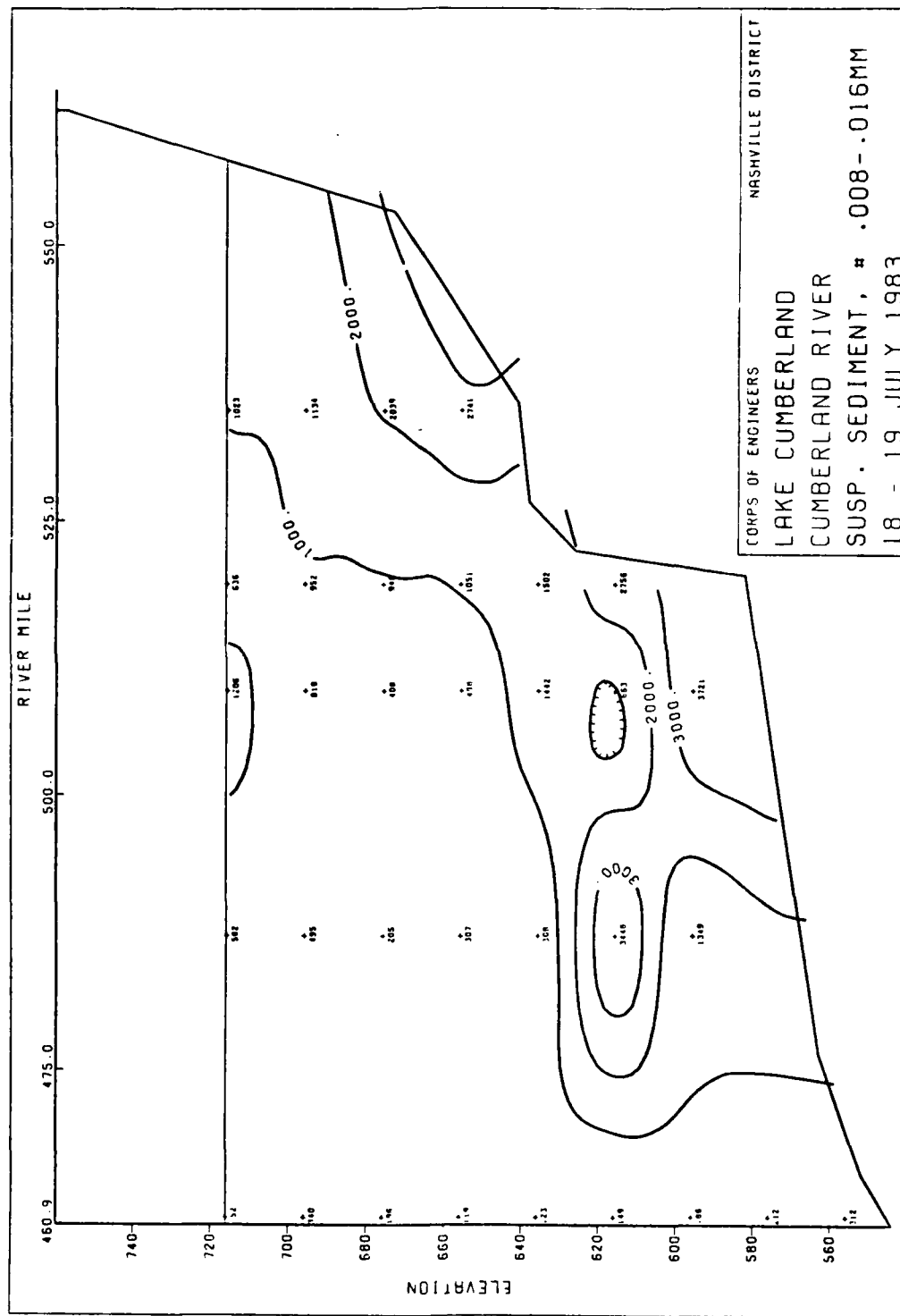


Figure 32. Number of Particles 8-16 μ m Particles During July Survey

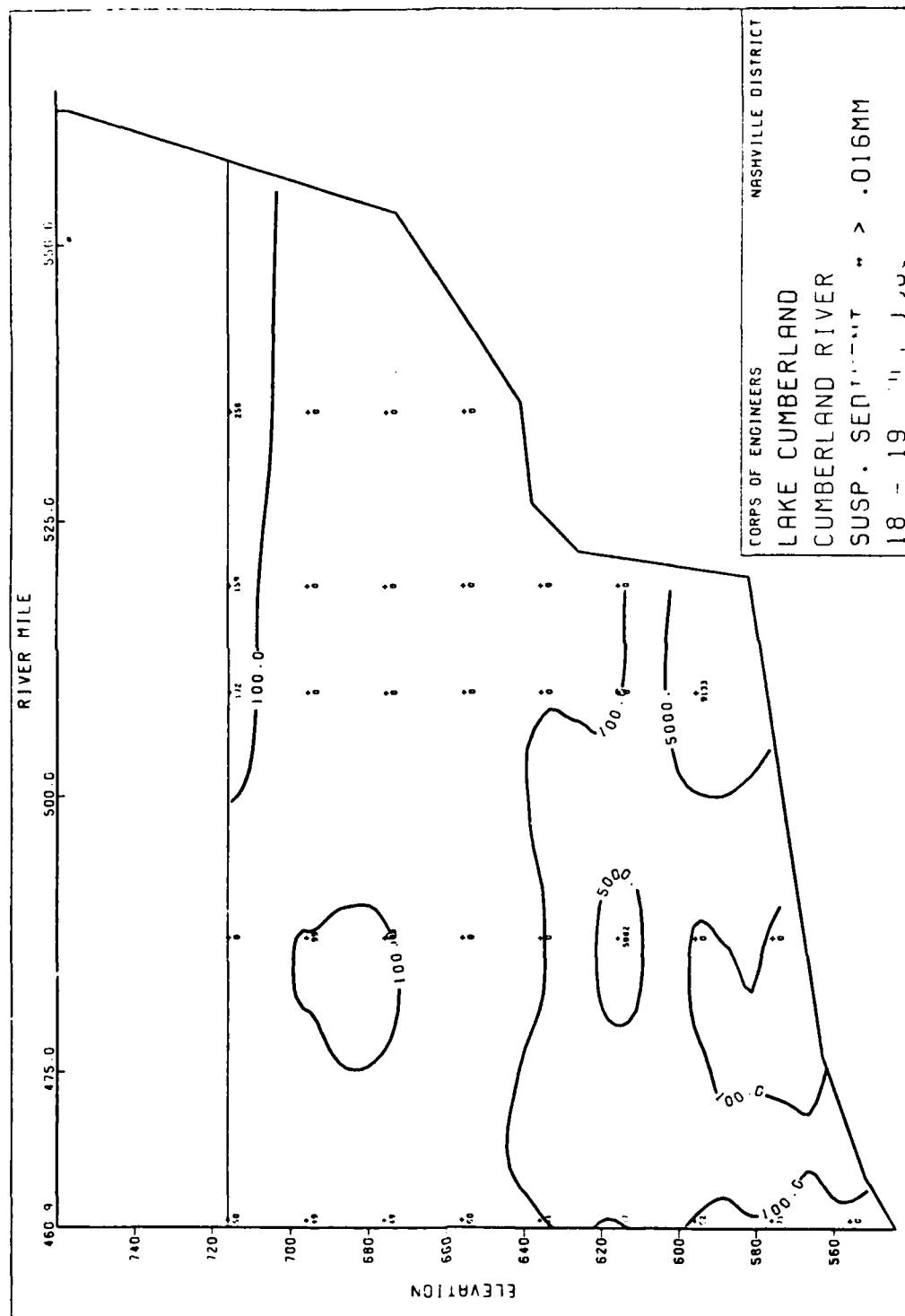


Figure 34. Number of Particles > 16 μ m Present During July Survey

that the particles which originated from the same source and same influx event shared similar electrical characteristics. Other than this, these plots did not provide much useful information. The range of zeta potentials did, however, have some very important implications. The zeta potentials over all six surveys ranged from -6.7 to -44.0 millivolts with the majority of values between -10 and -20 millivolts. Based on the general relationship between stability and zeta potential, Table 5 provides the stability characteristics expected from the zeta potentials measured on particles taken from Lake Cumberland. It should be pointed out that only the one sample had a value greater than -24.8 millivolts. Based on these values and the general relationship exhibited by Table 5, the particles present during this project were nearly all in a range where their charge would not significantly interfere with their coming together to form larger particles which could more quickly settle to the lake bottom [70]. This clearly demonstrated that colloidal charge is not the major reason particles settle so slowly in this lake.

Suspended Sediment Composition Tests

124. As the information from the previously discussed tests began to accumulate, further testing was initiated to learn more about the content of the particles which form the turbid layer. These tests included x-ray diffraction and determination of the suspended sediments' volatile content. The suspended sediment was also examined to determine the amount of iron present.

125. The initial predictions of the composition of these suspended particles tended to be centered around clay minerals. Since

Table 5. Stability and Zeta Potential Relationships

Stability Characteristics	Average ZP in Millivolts
Maximum agglomeration and precipitation	+ 3 to zero
Excellent agglomeration and precipitation	- 1 to - 4
Fair agglomeration and precipitation	- 5 to - 10
Threshold of agglomeration (agglomerates of 2 to 10 colloids)	-11 to - 20
Plateau of slight stability (few agglomerates)	-21 to - 30
Moderate stability (no agglomerates)	-31 to - 40
Good stability	-41 to - 50
Very good stability	-51 to - 60
Excellent stability	-61 to - 80
Maximum stability	-81 to -125

there are many types of clay minerals, it was hoped that by identifying the specific clay, the source of the turbid input could be located and possible remedial action taken to prevent future inflow. The identification of clay minerals was accomplished by use of x-ray diffraction. Over the course of the project, gallon jugs of water samples were taken from the turbid layer and evaporated to concentrate the suspended sediment. Slides were prepared from these samples and tested by x-ray diffraction along with a bentonite clay sample which had been prepared in the laboratory as an experimental control.

126. The x-ray diffraction unit recorded peaks at the appropriate slide angle for the identification of the prepared bentonite clay slide. The remaining samples, however, did not produce any reactions by the diffraction unit. This showed the initial prediction of clay particles to be false. A few sample slides did produce very small peaks which represented the presence of small quantities of quartz and gypsum or calcite. The sample slides were also tested after the addition of glycol to produce expansion of the lattice structure of any clays present. The peak produced by the bentonite control sample reacted accordingly by increasing in intensity. The remaining sample slides were again tested and showed no changes to have occurred. Based on these tests, the particulate matter suspended within Lake Cumberland was not composed of any type of clay. Conversely, this indicated that the particles must either be organic or amorphous material.

127. To determine if the suspended sediment might be some organic pollutant or seasonal growth of microorganisms, a test was conducted to determine the volatile content of the samples. In order to accomplish this, the sediment which remained after evaporation was

collected and weighed for each sample. This was followed by heating at approximately 600°C to oxidize any organic content present and reweighing. The difference in initial and final weights represents the organic or volatile portion of the sediment sample. The results of this test are presented in Table 6. Overall, the volatile or organic portion of the sediment ranged from 15% to 22.8% with an average value of 18.4%. This means that only about one-fifth of the sediment was organic, which could have been due to the presence of an organic coating such as with hydrophilic protective colloids. In this case, the organic coating may have formed around the surface of an inorganic, amorphous center particle.

128. In order to further identify the composition of the suspended sediment particles, one final test was conducted on the inorganic samples which remained after testing for volatile content. This test, to determine the iron content of the sample sediments, was included due to the presence of coal strip-mined areas within the upper drainage basin. The test was conducted using a flame atomic absorption spectrophotometer unit. The results of this test shown in Table 6 found the particles to be composed of from 4.8% to 32.9% iron with an average iron content of 13.5% before the removal of the volatile portion of the sediment. The percentage of iron found in the nonvolatile portion of the suspended sediment ranged from 6.1% to 40.6% with an average of 16.6% present in the samples. In an attempt to find the inflows which contained the higher iron contents, these results were listed by location, month, and sampling depth. From these figures, it appears likely that a source of inflow containing iron exists between river mile 509.3 and 519.0. This approximately ten-mile stretch of the lake

Table 6. Results of Volatile Solids and Iron Content Tests

Location River Mile	Month	Depth Feet	Percent Volatile	Percent Nonvolatile	% Fe in Nonvolatile Solids	% Fe in Suspended Particles
509.3	May	20	17.1	82.9	20.3	16.8
509.3	July	70	18.9	81.1	40.6	32.9
509.3	Aug.	60	22.8	77.2	21.3	16.4
509.3	Aug.	70	21.0	79.0	6.1	4.8
519.0	May	10	15.1	84.9	14.3	12.1
519.0	July	70	18.8	81.2	16.0	13.0
519.0	Aug.	70	20.4	79.6	7.7	6.1
534.8	July	50	16.1	83.9	11.2	9.4
534.8	Aug.	30	19.4	80.6	8.0	6.4
BSF 2.3	July	70	15.0	85.0	7.2	6.1
BSF 2.3	Aug	70	18.7	81.3	13.4	10.9
Turbid Shoreline #56		1	17.6	82.4	31.4	25.9
Turbid Shoreline #89		1	18.6	81.4	17.8	14.5
N/A	N/A	N/A	18.4	81.6	16.6	13.5

contains two possible sources of this increased iron content: the flow from Pitman Creek and the water released from the cooling water or tailings pond of the coal-fired power plant located near river mile 517.

129. The results of both the test for iron and volatile solids content were obtained from the evaporated sediment samples remaining after x-ray diffraction slides had been prepared. Since these tests had not been planned to be part of the original project and the evaporation of the sample was of primary concern, the evaporation containers were not protected from contamination while inside the drying oven. Prior to the preparation of the x-ray diffraction slides, rust particles were observed and removed by magnet from the evaporating containers of some samples. These samples were for river mile 509.3, July survey at 70 feet, and river mile 534.8, July survey at 50 feet. Iron particles were also removed from one of the turbid shoreline samples. For this reason, the results of the iron test cannot be considered very accurate. The iron particles which were removed from the sediments were probably formed by precipitation as the iron concentration increased in the samples as evaporation progressed. It is possible, but less likely, that the rust originated from the steel racks inside the otherwise stainless steel oven. Based on these results, it appears that further study of iron concentrations within the lake may be warranted.

Summary

130. The results that have been presented and discussed have provided a great deal of information about reservoir hydrodynamics within Lake Cumberland. The suspended sediment dynamics have been

demonstrated and the suspended particles present have been characterized.

131. The figures which displayed the turbidity results showed the inflowing turbidity acted as a density interflow. When compared with the temperature figures, the contours in the turbidity figures displayed slow settling attributed to thermal-layer subsidence and suspended particle settling. These turbidity figures also showed the layer of high turbidity to thicken as it dropped in elevation. This thickening represented the variation in settling velocities by particle sizes. The faster settling velocities of the larger particles was confirmed by an examination of the figures for the suspended solids test results.

132. An examination of the electrical repulsive forces between the particles showed the average particle charge to be insufficient for producing a stable suspension. The results of the particle-size distribution test indicated that the majority of the particles were in the size range of 1 to 10 μm where slow settling is expected. The combination of the inadequate electrical charge and the particle-size information confirmed that the turbidity layer subsidence was due to the slow settling of the suspended particles composing that layer.

133. A comparison of the number of particles present within different size ranges indicated that particles greater than 8 μm were removed soon after entering the lake. The particles ranging in size from 2 to 8 μm tended to remain suspended for long periods of time while undergoing slow settling. A comparison of the actual particle counts for the size ranges up to 8 μm displayed decreasing concentrations with time. This was due to the rapid removal of a substantial number of

small particles which, due to the lack of repulsive charge, combine or flocculate to form larger particles having greater settling velocities.

134. The results of the x-ray diffraction test determined that the suspended sediment was not clay. Further testing revealed the suspended sediment to be approximately 20% organic and 80% inorganic. This indicated that the particles were composed of amorphous material. The organic material was believed to be an organic coating or protective colloid. Testing of the inorganic portion of the suspended sediment indicated the presence of a significant amount of iron.

Test Correlations

135. With the abundance of data collected during this project, detailed comparisons of some of the test results obtained were possible. These comparisons were carried out to evaluate the differences, the similarities, and the possibility of substituting or using one test's results to predict other parameters. The tests compared here were turbidity versus suspended solids and turbidity versus number of particles.

Turbidity versus Suspended Solids

136. Much has already been written about these tests and about how they may compare. These are very different measurements, one of which measures the weight of suspended material large enough to be retained by a filter while the other, turbidity, measures scattered light. There is some slight physical relationship between the two. Suspended solids represent a portion of the size distribution of particles present which are able to scatter light. The literature

reports that the composition of the suspended material should be fairly consistent throughout the size distribution for any single system. This allows the particle weight and size relationship to be considered directly proportional. Since the percentage of each range in a size distribution has been shown to remain relatively constant for each individual inflow event, it appeared reasonable that the relationship between turbidity and the volume of material over the entire size distribution which causes that turbidity would also exist between turbidity and suspended solids.

137. A comparison of figures for turbidity and suspended solids over the course of the project clearly demonstrated that such a relationship existed. This relationship is very weak to nonexistent, however, for turbidities of less than about 20 NTU. This weakness over low turbidity ranges was due to the inaccuracies involved in testing and weighing very small amounts of suspended solids. As the measured amounts increased, this source of error became a smaller, less important portion of the total suspended solids value. The turbidity value at which this relationship begins to erode appeared to be variable. This was due to the turbidity measurements' reliance on both particle size and number whereas suspended solids measurements are solely dependent on particle size. For this reason, any relationship established between turbidity and suspended solids would be useful for only immediate use before coagulation and settling could occur within the system.

Turbidity versus Particle Count

138. The relationship between turbidity and number of particles also appears to be very strong. Any comparison between particles and

turbidity, however, is a dangerous thing to attempt without always remembering the different basis of the measurements. If one considers only monosize particles having the same light reflectance characteristics, a relationship between number of particles and turbidity should be easy to establish. The turbidity which results from one particle should increase as more particles are introduced. The increase in turbidity should be proportional to the number of particles added. In the measurement of turbidity, light is being passed through a three-dimensional area filled with a water sample. If the third dimension of depth is ignored, the light is being blocked to some extent by particles in a two-dimensional cross section. Assuming that three particles resulted in one unit of turbidity, the number of particles needed to increase the turbidity another unit should lie between twice the original number and the original number of particles squared. If the dimension of depth is included, the number of particles required might range up to the original number cubed. In considering depth, other factors enter into the situation which reduce the effect of a third dimension. These factors are the apparent size reduction of even monosize particles at a distance from the light source and the reflectance light from the back side of particles which result in a decrease in the amount of light which appears to be blocked.

139. Based on these considerations, graphs were constructed for the various surveys to determine which mathematical equation could be used to accurately approximate the relationship between the number of particles and turbidity. In addition to searching for this relationship, the particle-count and size-distribution data were utilized in an attempt to establish a connection between turbidity and

the number of particles in a specific size range. The graphs which were constructed eliminated the possibility of any typical logarithmic relationship (semi-log, log-log) existing. The possibility of a direct or multiple type of relationship was checked by regression analysis of the total number of particles versus turbidity. For some surveys, this produced a high coefficient of correlation while for others a very poor coefficient was calculated. This ruled out any doubling relationship since this would only change the slope by a factor of two. In testing for square or cube root relationships, three particle-size ranges were used: 2-5 μm , 2-8 μm , and 2-10 μm . Although the cube root relationship maintained a high correlation coefficient, that of the square root relationship was consistently higher. The results of the different size ranges tested for the square root relationship showed some variation over the surveys, but the 2-8 μm range usually resulted in the higher correlation coefficients, all of which were above 0.90. A typical example of this relationship is presented as Figure 35. This small variation in the best size range would be expected since the surveys did not test the same inflow event distributions. The slope and intercept also showed slight changes for each different survey for this same reason with the slope clearly displaying a gradual increase over each month.

140. As a result of these tests, the best method of predicting particle counts from turbidity or converting between the two test methods was established. It should be remembered that the use of this information would be limited to the Lake Cumberland system with best results obtained when a fairly current relationship has been established. The gradual increase in slopes through the season probably

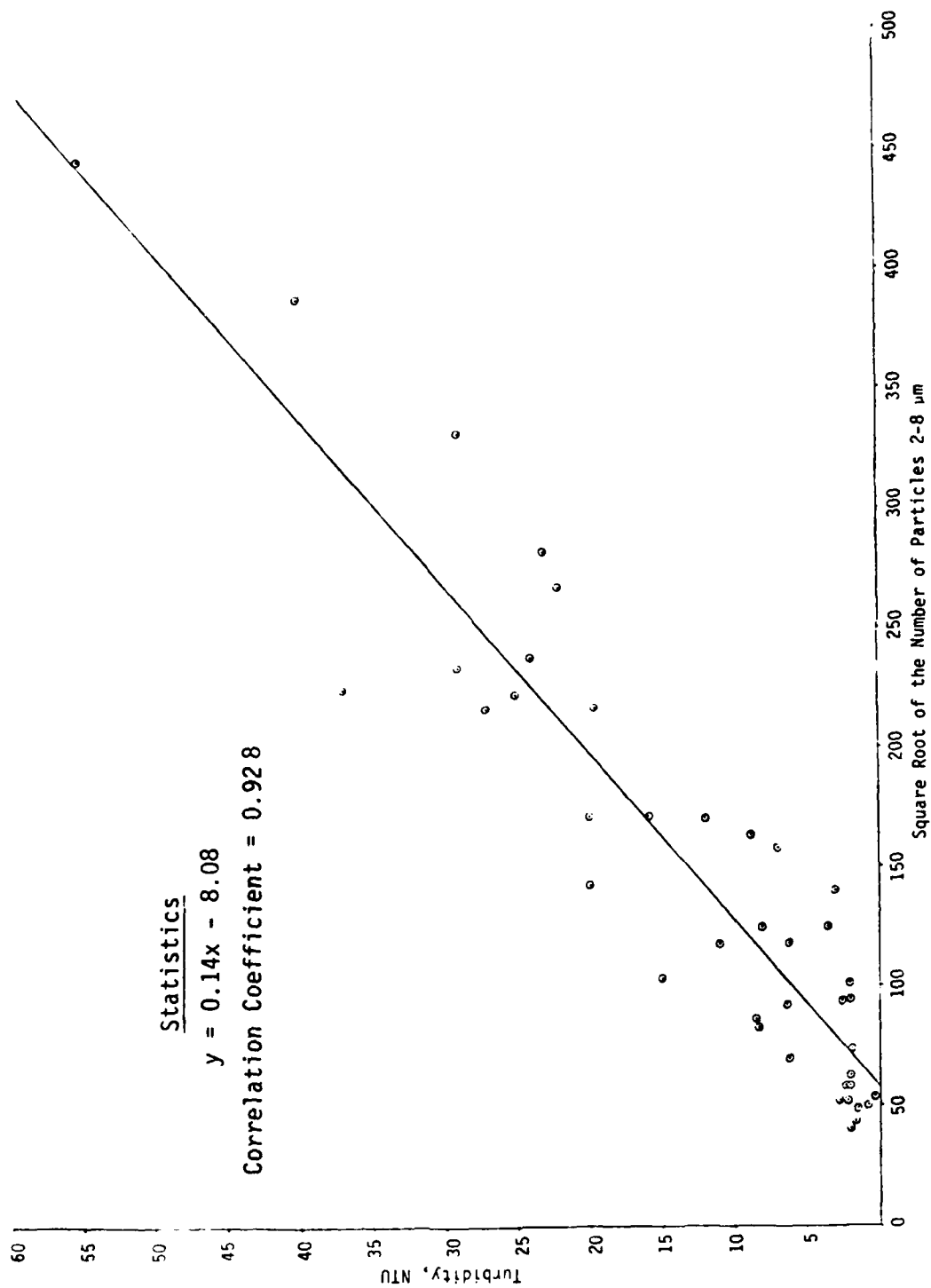


Figure 35. Turbidity vs. Square Root of Particles 2-8 μm, July 1983 Survey

indicates a shift in the size of the particles causing turbidity. If this gradual change in the relationship could be established over a number of seasons, a reasonably accurate model of the turbidity and particle number relationship could be constructed for Lake Cumberland.

Part V: SITUATION ANALYSIS AND MANAGEMENT IMPLICATIONS

141. The formation and movement of a turbidity layer over the length of the lake, and occasionally through the dam, seem to be a consistent annual event. This occurrence is the result of a combination of factors. Many of these factors, such as the settling velocity of the turbidity plume or the time of year that the turbid inflow occurs, cannot be managed or controlled by the operation of the reservoir. Other influences can be controlled. If the objective is the containment and sedimentation of the turbid inflow within Lake Cumberland, a complete understanding of the plume dynamics is required. Based on this information, a management plan can be developed which minimizes the probability of the turbidity being passed through the dam.

Situation Analysis

142. When a storm event occurs, the sediment-laden runoff drains into the tributaries throughout the upper drainage basin. This increased flow in these restricted channels raises the velocity of the inflow to the lake. The momentum of the fast-flowing turbid runoff forces itself into the upper portion of the lake. Mixing is limited, however, due to density differences. This results in an increase in water elevation through the lake with previously impounded water being forced into the lower length of the lake and the turbid runoff occupying the upper end. Since mixing is limited, the turbid inflow begins to seek out and enter its density layer in the previously impounded stratified water. This insertion as a density layer results in the

turbid inflow taking on the form of a turbidity plume. At this point, the input momentum eventually becomes balanced by the resistance to flow of the neighboring waters. The particles which comprise the turbidity plume and which have been moving with the inflow waters are then allowed to settle at their individual settling rates.

143. This description of the input of turbid waters has not yet explained the method by which the layer reaches and passes through the dam. The reason that this can occur is solely due to the release of water from the dam through normal operation. Releases from the dam are accomplished by two methods, gate releases of the surface waters and turbine or generator releases for the production of hydroelectric power. Both of these methods of release and their implications on turbid-layer movement have been thoroughly discussed. The operation of surface gates tends to pull the turbid inflow towards the dam. Turbine releases cause layer subsidence which, while dropping the elevation of the plume, also causes movement toward the dam. In the event that no releases are required, when the momentum reaches zero any other advances toward the dam would be due to further density gradient insertion and layer diffusion.

144. The factors which cannot be controlled but which influence the ability of the plume to reach the dam are: the timing of the runoff event, the degree of stratification present at the time of the runoff, and the position of the plume when the momentum is dissipated. The time of the runoff event determines the time that the turbid flow will be retained in the lake. Sedimentation will occur during this retention time. The degree of stratification present at the time of the runoff event determines the extent to which the turbid inflow will initially

advance through the lake towards the dam. The position of the plume when the momentum equals zero is a function of the momentum produced by the intensity and volume of the storm causing the runoff event. Another factor which is to a large extent uncontrollable is the volume of water which must be released to meet hydroelectric power demands and flood control requirements.

145. Another reason that sediments are able to pass through the lake is the size and shape of the reservoir. In most other lakes and reservoirs, their size and shape aid in the sedimentation process. This is not the case at Lake Cumberland. The shape of the reservoir is very much like that of a bathtub with steep, sheer sides and a wide, flat, deep bottom. Even the upper portion of the lake begins with a steep decline instead of the gradual sloping inflow areas present in other lakes. This all results in the lake providing almost no sloping side banks for the disposition of sediment upon entry and such a slight, gradual velocity reduction that sediment may remain suspended over long distances and times. When sedimentation does occur, it demonstrates a sorting phenomenon along the length of the lake with gradually decreasing sizes of particles reaching the bottom. The shape and depth of the lake also allows resuspension of particles to occur. Continued suspension is promoted by the vast areas of water which can be affected by wave motion caused by wind action and/or internal current movement. It is this relatively unique shape which allows these other factors to exert such a great influence over the final destination of the inflowing sediments.

Management Implications

146. From the information gathered, a management plan can be developed which reduces the possibility that turbid waters will be released downstream. The basic premise of such a plan would be the retention of as much water as feasible immediately after the occurrence of a runoff event which produces a highly turbid inflow. Until the turbidity plume formed has settled to an elevation below that of the generator inlets, all necessary releases should be restricted to turbine releases, except in emergency situations. By operating the reservoir in this fashion, the turbidity could be contained and provided with a situation conducive to sedimentation. The inclusion of multilevel withdrawal capabilities at Wolf Creek Dam would greatly enhance this ability. If a problem develops with increased turbidity in releases downstream, other remedial measures such as the construction of subsurface dams might be considered to aid in sediment removal within the lake.

PART VI: CONCLUSIONS

147. A number of conclusions can be drawn from the results of the tests conducted during this project. These conclusions include determinations about the suspended sediment particles themselves and the dynamics of the reservoir which influence their movement as a layer. A number of judgments concerning the benefits and interactions of the tests used during this project have also been included.

Suspended Sediment Particle Characteristics

148. The characteristics of the suspended sediment particles were found to be as follows:

- a. X-ray diffraction studies indicate the particles to be amorphous in nature.
- b. Based on this amorphous structure the specific gravity of the particles is estimated to be less than that of clay minerals and ranges from approximately 2.2 to 2.4.
- c. The particles comprising the turbidity plume range in size from approximately 2 to 8 μm . Within this size range, slow settling occurs.
- d. Results of the zeta potential test indicate the particles to have a weak charge which is insufficient, in itself, to cause colloidal suspension.
- e. The volatile portion of the suspended sediments averaged 18.4% with a range of 15% to 22.8%. This portion is

considered to be totally organic.

- f. The suspended sediments appear to have a substantial iron content.

Reservoir Dynamics and Turbidity Layer Movement

149. The following observations were made concerning reservoir dynamics and turbidity layer movement within Lake Cumberland.

- a. During 1983, the turbid plume entered the lake with a cross section ranging from the water's surface to approximately 40 feet in depth. This resulted in settling depths of approximately 120 to 150 feet in the reservoir below the Burnside Bridge located at river mile 511.
- b. Some sediment appears to be swept off the underwater plateau located around river mile 528 and resuspended in the lake.
- c. The rate at which the turbid layer moves toward the dam is a function of the method of release. Gate releases tend to short circuit or pull the plume downstream faster than turbine releases which gradually allow the layer to enter and traverse the lake.
- d. The plume will tend to be diluted or reduced in intensity by:
 - (1) settling of larger particles,
 - (2) lateral diffusion of the layer over the width of the lake, and
 - (3) downstream density flows and the resulting mixing and dispersion.
- e. The primary factors which determine if the turbid layer reaches the dam are:
 - (1) season or month of the runoff event,

- (2) degree of stratification present during the inflow,
 - (3) temperature of the turbid inflow,
 - (4) method of reservoir operation during and after the runoff event,
 - (5) volume of the turbid inflow,
 - (6) position of the turbidity plume when input momentum equals zero, and
 - (7) subsequent hydroelectric volume requirements.
- f. When the input momentum equals zero, the plume begins to settle. The settling rate is governed by particle size and mass plus layer subsidence due to turbine releases during periods of stratification. The turbid layer settled faster than layer subsidence in 1983. Settling velocities of 0.67 ft/day without subsidence and 1.17 ft/day with turbine releases were calculated for the turbidity plume. These velocities result in periods greater than approximately 103 days or 3½ months being required for the plume to impact the lake bottom.
- g. The main reason turbid water is able to reach the dam is the fairly unique shape of the reservoir below, and to some extent above, Burnside, Kentucky. The rectangular shape and overall depth require exceptionally long settling times for the removal of sediments within the turbidity layer. The near vertical side slopes of the lake prevent removal and allow incoming sediment to be distributed over most of the reservoir. As a result of this shape, sediment settles out uniformly over the length of the lake.

Survey Conclusions

150. The following conclusions were reached concerning the testing methods employed in this survey.

- a. Turbidity is the easiest, quickest, most reliable, and most informative test which can be used in the survey of reservoir hydrodynamics.
- b. The combined use of turbidity and temperature information can serve as the basis for hydrodynamic modeling of a reservoir system.
- c. Turbidity is related to both suspended solids and the number of particles present. These relationships, however, are applicable only to the system for which they were derived and are constantly undergoing changes.

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